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How Old is the Earth

A Response to "Scientific" Creationism

by G. Brent Dalrymple

Contents

How Old is the Earth
A Response to "Scientific" Creationism

by G. Brent Dalrymple,
U.S. Geological Survey
Menlo Park, California

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Other Links:

Radiometeric Dating Does Work!

Another article by the author, from the year 2000.

A Radiometric Dating Resource List

A useful list of resources related to radiometric dating including what is wrong with the arguments of the young-earth creationists.

Age of the Earth FAQ

This Archive's FAQ on the age of the Earth.

Also see: Detailed Contents

INTRODUCTION

The proponents of "scientific" creationism (for example, 54, 77, 90, 92, 95, 96, 135) claim to have developed a legitimate scientific model for the creation and history of the universe that explains extant scientific observations as well as, if not better than, the current theories and concepts of biology, chemistry, physics, geology, and astronomy. Even a cursory reading of the literature of "scientific" creationism, however, reveals that the creation model is not scientifically based but is, instead, a religious apologetic derived from a literal interpretation of parts of the book of Genesis. Indeed, this literature abounds with direct and indirect references to a Deity or Creator, and citations of the Bible are not uncommon (for example, 22, 77, 90, 91, 96, 97, 99, 131).

The tenets of "scientific" creationism include the beliefs that the Earth, the Solar System, and the universe are less than 10,000 years old (13, 77, 92, 116, 117) and that nearly all the sedimentary rocks on the Earth were deposited in about one year during a worldwide flood (29, 77, 92, 131). Both of these propositions are disproved by a vast and consistent body of scientific evidence.

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 billion years old, that the oldest rocks on the Moon are 4.4 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 (Figure 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 spite of massive evidence to the contrary, creation "scientists" continue to defend their belief in a very young Earth. Their arguments fall generally into two categories: The first involves criticisms of radiometric dating techniques and data; the second involves various calculations that they claim provide quantitative evidence that the Earth is young. In this paper I explain briefly how radiometric dating methods work and the principal evidence that the Earth is 4.5 to 4.6 billion years old. I also examine in detail some examples of the creationists' criticisms and calculations and show that they are scientifically meaningless.

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 (61). Ages are based on the new decay constants adopted by the International Union of Geological Sciences.

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 The Precambrian is the time between the origins of the Earth and the beginning of the Cambrian period.				4,550

Dedication and Acknowledgments

I dedicate this paper to the memory of Max Crittenden, who died of cancer on Thanksgiving Day, 1982. Max was not only a friend and colleague, but was a leader in the effort to preserve the integrity of California science textbooks against the creationists' attack in the early 1970s. Max was a constant source of encouragement and support in many matters, but especially in my efforts to expose the glaring errors in the creationists' propaganda about the scientific evidence for the age of the Earth and the vastness of geologic time.

I thank my friends and colleagues Patrick Abbott, Calvin Alexander, Frank Awbrey, Arthur Boucot, Stephen Brush, Max Crittenden, Norman Horowit, Thomas Jukes, Arthur Lachenbruch, Marvin Lanphere, Robert Root-Bernstein, John Sutter, and Christopher Weber, who read an early draft of the manuscript and offered valuable comments, suggestions, and encouragement.

The question of the ages of the Earth and its rock formations and features has fascinated philosophers, theologians, and scientists for centuries, primarily because the answers put our lives in temporal perspective. Until the 18th century, this question was principally in the hands of theologians, who based their calculations on biblical chronology. Bishop James Ussher, a 17th-century Irish cleric, for example, calculated that creation occurred in 4004 B.C. There were many other such estimates, but they invariably resulted in an Earth only a few thousand years old.

By the late 18th century, some naturalists had begun to look closely at the ancient rocks of the Earth. They observed that every rock formation, no matter how ancient, appeared to be formed from still older rocks. Comparing these rocks with the products of present erosion, sedimentation, and earth movements, these earliest geologists soon concluded that the time required to form and sculpt the present Earth was immeasurably longer than had previously been thought. James Hutton, a physician-farmer and one of the founders of the science of geology, wrote in 1788, "The result, therefore, of our present inquiry is, that we find no vestige of a beginning, — no prospect of an end." Although this may now sound like an overstatement, it nicely expresses the tremendous intellectual leap required when geologic time was finally and forever severed from the artificial limits imposed by the length of the human lifetime.

By the mid- to late 1800s, geologists, physicists, and chemists were searching for ways to quantify the age of the Earth. Lord Kelvin and Clarence King calculated the length of time required for the Earth to cool from a white-hot liquid state; they eventually settled on 24 million years. James Joly calculated that the Earth's age was 89 million years on the basis of the time required for salt to accumulate in the oceans. There were other estimates but the calculations were hotly disputed because they all were obviously flawed by uncertainties in both the initial assumptions and the data.

Unbeknownst to the scientists engaged in this controversy, however, geology was about to be profoundly affected by the same discoveries that revolutionized physics at the turn of the 20th century. The discovery of radioactivity in 1896 by Henri Becquerel, the isolation of radium by Marie Curie shortly thereafter, the discovery of the radioactive decay laws in 1902 by Ernest Rutherford and Frederick Soddy, the discovery of isotopes in 1910 by Soddy, and the development of the quantitative mass spectrograph in 1914 by J. J. Thomson all formed the foundation of modern isotopic dating methods. But it was not until the late 1950s that all the pieces were in place; by then the phenomenon of radioactivity was understood, most of the naturally occurring isotopes had been identified and their abundance determined, instrumentation of the necessary sensitivity had been developed, isotopic tracers were available in the required quantities and purity, and the half-lives of the long-lived radioactive isotopes were reasonably well known. By the early 1960s, most of the major radiometric dating techniques now in use had been tested and their general limitations were known.

No technique, of course, is ever completely perfected and refinement continues to this day, but for more than two decades radiometric dating methods have been used to measure reliably the ages of rocks, the Earth, meteorites, and, since 1969, the Moon.

Radiometric dating is based on the decay of long-lived radioactive isotopes that occur naturally in rocks and minerals. These parent isotopes decay to stable daughter isotopes at rates that can be measured experimentally and are effectively constant over time regardless of physical or chemical conditions. There are a number of long-lived radioactive isotopes used in radiometric dating, and a variety of ways 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 listed in Table 1. Sometimes these decay schemes are used individually to determine an age (e.g., Rb-Sr) and sometimes in combinations (e.g., 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 accumulate in this short time. Likewise, the ^{14}C method can only be used to determine the ages 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.[1] The point is that not all methods are applicable to all rocks of all ages. One of the primary functions of the 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. Some of the methods have internal checks, so that the data themselves provide good evidence of reliability or lack thereof. Commonly, a radiometric age is checked by other evidence, such as the relative order of rock units as observed in the field, age measurements based on other decay schemes, or ages on several samples from the same rock unit. The main point is that the ages of rock formations are rarely based on a single, isolated age measurement. On the contrary, radiometric ages are verified whenever possible and practical, and are evaluated by considering other relevant data.

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}O)	lead-207 (^{207}Pb)	7.04×10^{8}
uranium-238 (^{238}O)	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}

My purpose here is not to review and discuss all of the dating methods in use. Instead, I describe briefly only the three principal methods. These are the K-Ar, Rb-Sr, and U-Pb methods. These are the three methods most commonly used by scientists to determine the ages of rocks because they have the broadest range of applicability and are highly reliable when properly used. These are also the methods most commonly criticized by creation "scientists." For additional information on these methods or on methods not covered here, the reader is referred to the books by Faul (47), Dalrymple and Lanphere (35), Doe (38), York and Farquhar (136), Faure and Powell (50), Faure (49), and Jager and Hunziker (70), as well as the article by Dalrymple (32).

THE K-Ar METHOD

The K-Ar method is probably 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 is relatively abundant, it is usually not possible to correct for the ^{40}Ca initially present and so 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 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[2] 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 due to atmospheric contamination. What is left is the amount of 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 principal requirements. 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 past 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 not on other minerals, such as feldspar from granite rocks, because they leak their argon even at low temperatures. The method works well on subaerial lava flows, but not on most submarine pillow basalts because they commonly 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 do occur but they are usually caught by the various checks employed in the well-designed experiment.

THE Rb-Sr 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. Rubidium is a major constituent of very few minerals, but the chemistry of rubidium is similar to that of potassium and sodium, both of which do form many common minerals, and so 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 so 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.

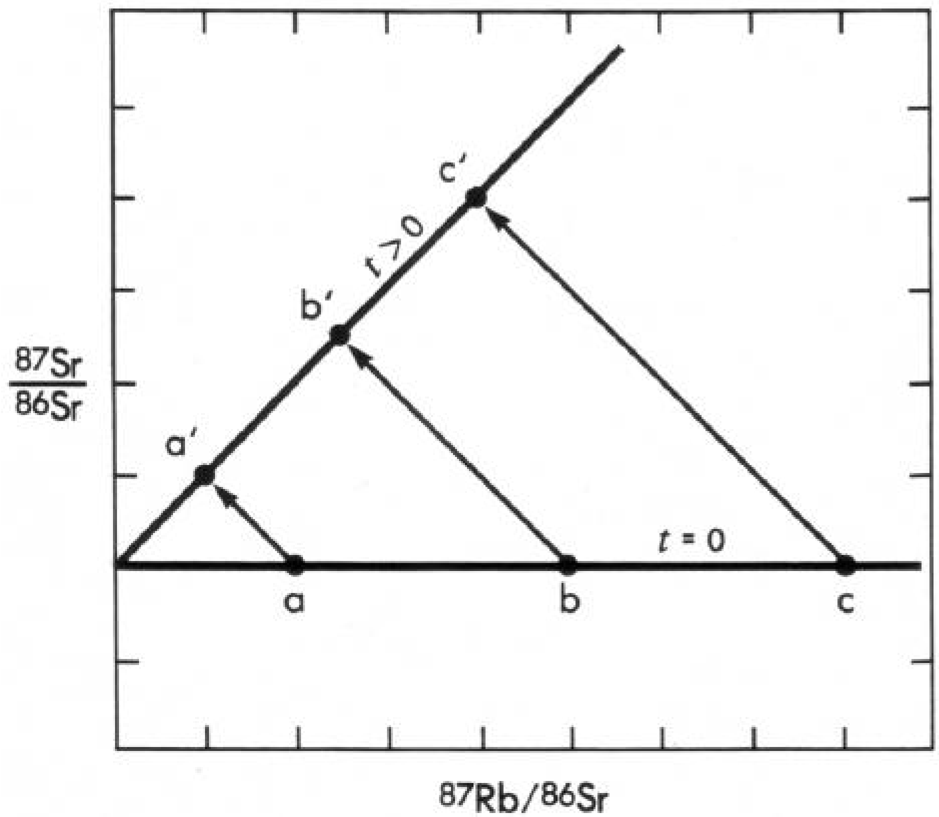
Unlike argon, which escapes easily and entirely from most molten rocks, strontium is present as a trace element in most minerals when they form. For this reason, simple Rb-Sr ages can be calculated only for those minerals that are high in rubidium and contain a negligible amount of initial strontium. In such minerals, the calculated age is insensitive to the initial strontium amount and composition. For most rocks, however, initial strontium is present in significant amounts, so dating is done by the isochron method, which completely eliminates the problem of initial strontium.

Other Links:

Isochron Dating
Chris Stassen shows how isochron dating works.

In the Rb-Sr isochron method, several (three 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 (Figure 2). The ^{87}Rb and ^{87}Sr contents are normalized to the amount 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 Figure 2). 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[3] shown by the arrows. At any time after formation, the points will lie along some line a'-b'-c' (Figure 2), whose slope will be a function of the age of the rock. The intercept of the line on the ordinate gives the isotopic composition of the initial strontium present when the rock formed. Note that the intercepts of lines a-b-c and a'-b'-c' are identical, so the initial strontium isotopic composition can be determined from this intercept regardless of the age of the rock.

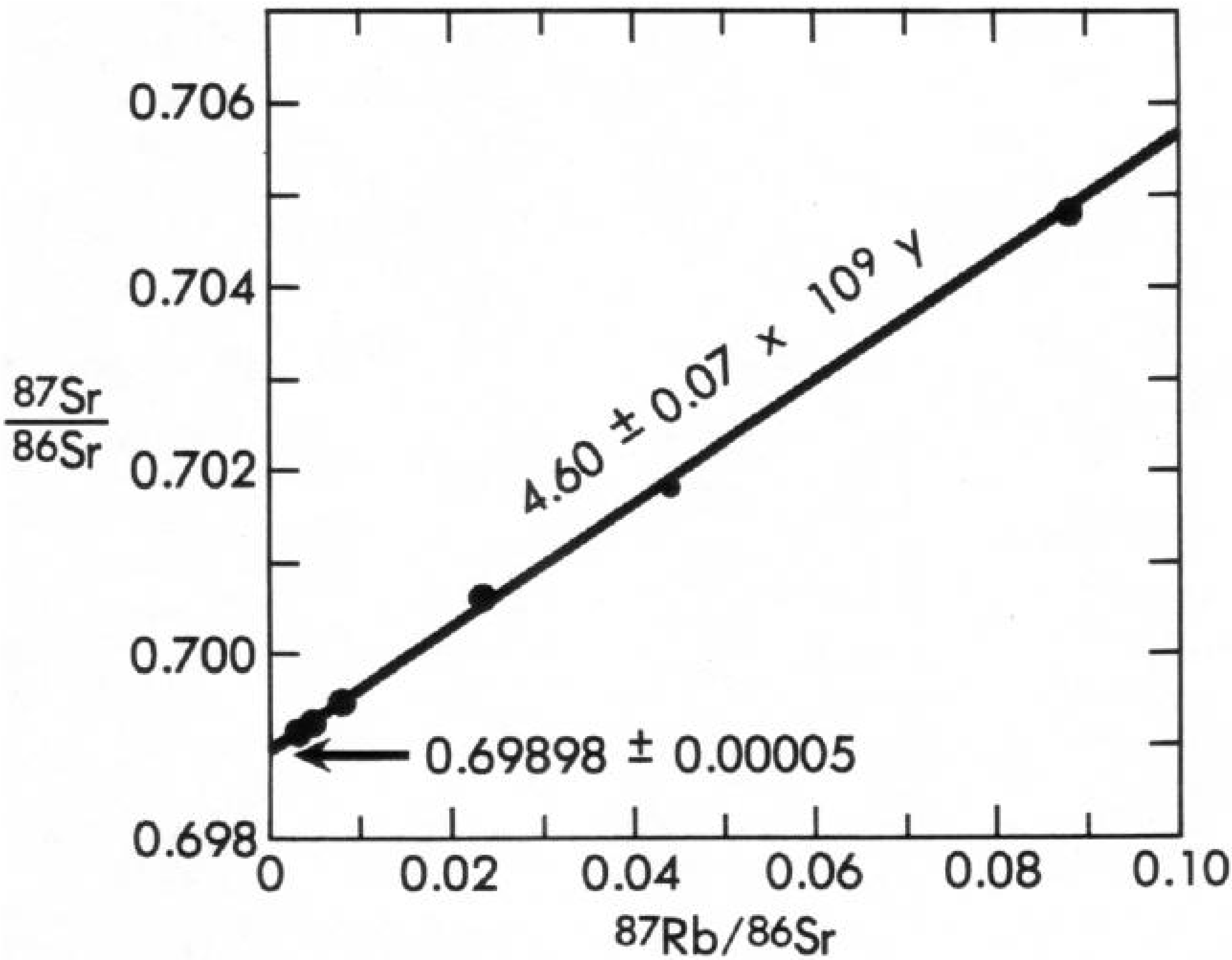
Figure 2: Rb-Sr isochron diagram, showing the time-dependent evolution of Rb and Sr isotopes in a closed system. After Faure (49).



Note that the Rb-Sr isochron method requires no knowledge or assumptions about either the isotopic composition or the amount of the initial daughter isotope — in fact, these are learned from the method. The rocks or minerals must have remained systems closed to rubidium and strontium since their formation; 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 data 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 3, which includes analyses of five separate phases from the meteorite Juvinas (3). 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 (84).

Figure 3: Rb-Sr isochron for the meteorite Juvinas. The points represent analyses on glass, tridymite and quartz, pyroxene, total rock, and plagioclase. After Faure (49). Data from Allegre and others (3).



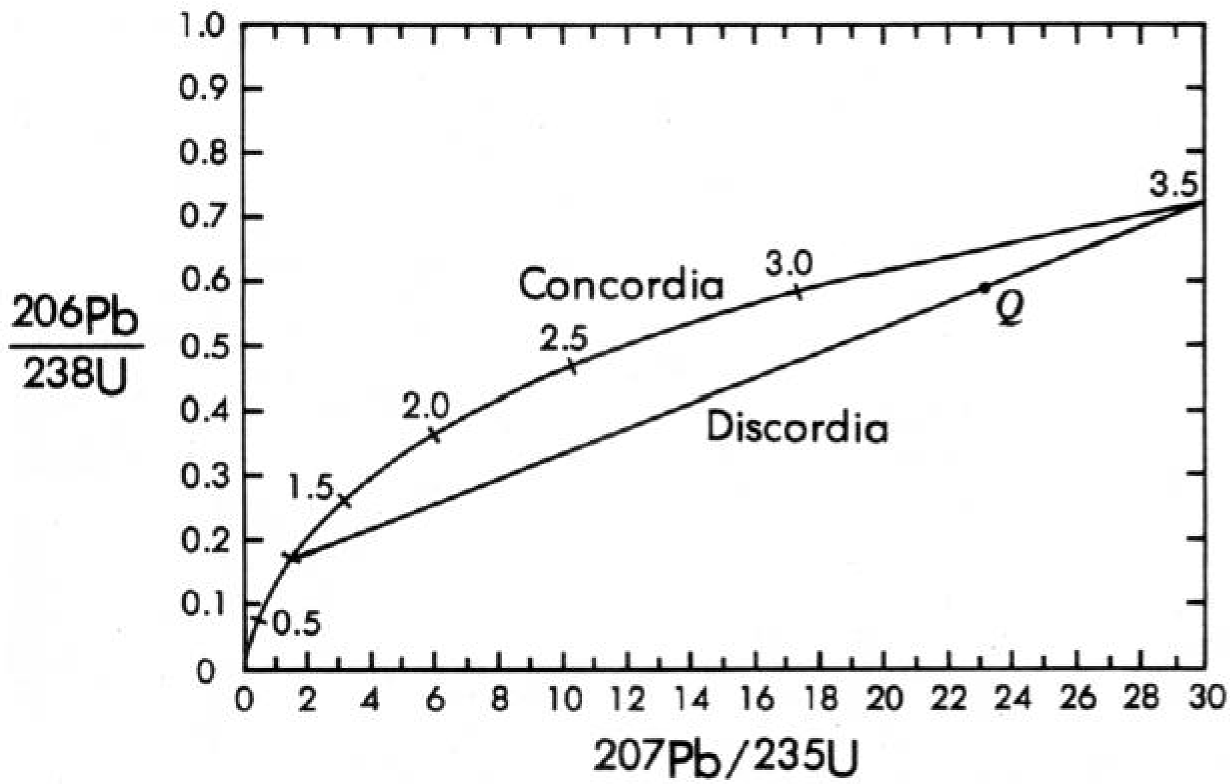
THE U-Pb METHOD

The U-Pb method relies on the decays of ^{235}U and ^{238}U. These two parent isotopes undergo series decay involving several intermediate radioactive daughter isotopes before the stable daughter product, lead (Table 1), is reached.

Two simple independent "age" calculations can be made from the two U-Pb decays: ^{238}U to ^{206}Pb, and ^{235}U to ^{207}Pb. In addition, an "age" based on the $^{207}Pb/^{206}Pb$ ratio can be calculated because this ratio changes over time. If necessary, a correction can be made for the initial lead in these systems using ^{204}Pb as an index. If these three age calculations agree, then the age represents the true age of the rock. Lead, however, is a volatile element, and so lead loss is commonly a problem. As a result, simple U-Pb ages are often discordant.

The U-Pb concordia-discordia method circumvents the problem of lead loss in discordant systems and provides an internal check on reliability. This method involves the ^{238}U and ^{235}U decays and is used in such minerals as 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 point representing the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios will plot on a curved line known as concordia (Figure 4). 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 later), the point Q in Figure 4 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 4. There are several hypotheses for the interpretation of the lower intercept, but the most common interpretation is that it indicates the age of the event that caused the lead loss, or 1 billion years in Figure 4. 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 its loss does not seem to be a problem. If uranium were lost, however, the concordia-discordia plot would indicate that also.

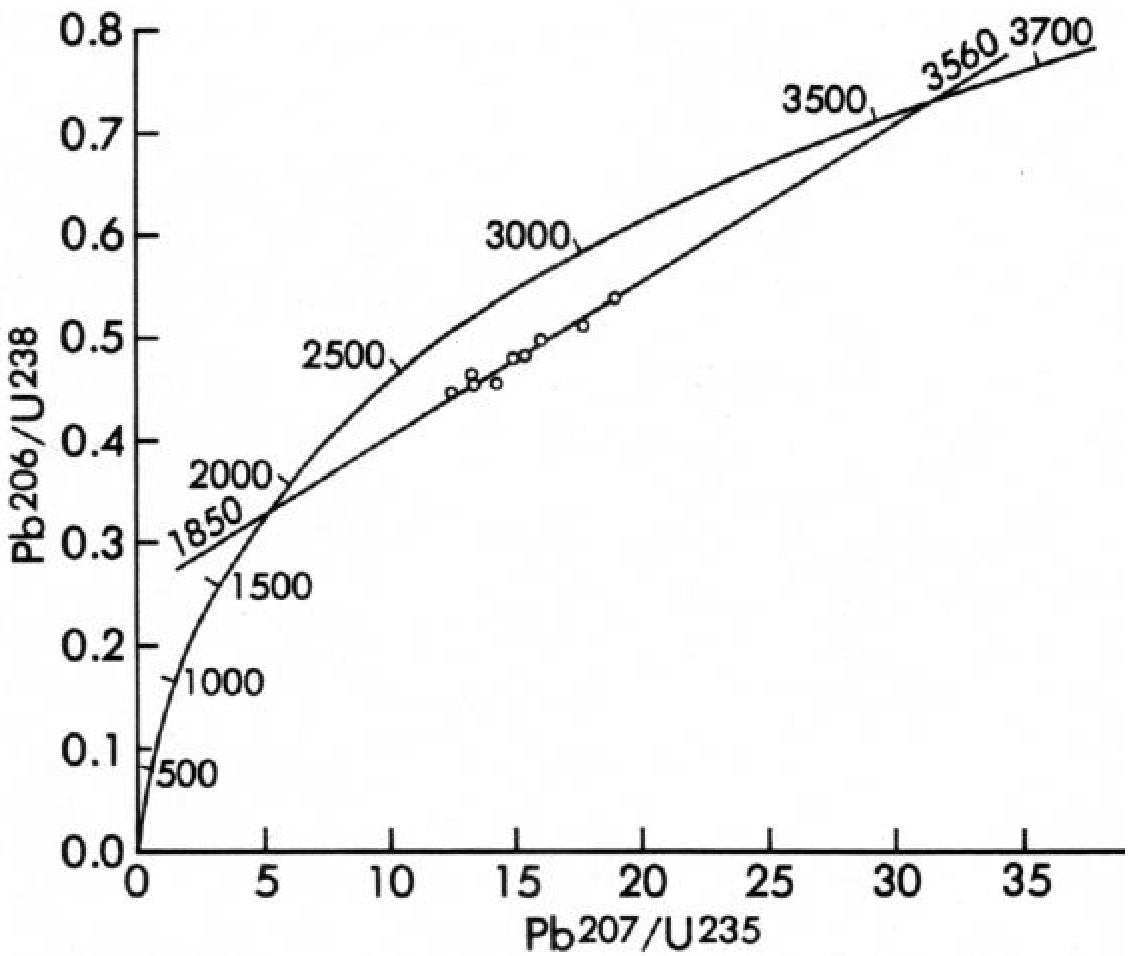
Figure 4: U-Pb concordia-discordia diagram showing the evolution of a system that is 3.5 billion years old and underwent episodic lead loss 1.0 billion years ago. See text for explanation. After Faure (49).



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 useful in rocks with complex histories. Quite often this method is used in conjunction with the K-Ar and the Rb-Sr isochron methods to unravel the history of metamorphic rocks, because 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, which is 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 Figure 5. 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 experience by these rocks. The K-Ar ages on rocks and minerals from this area in southwestern Minnesota also record this 1.85-billion-year heating event.

Figure 5: U-Pb concordia-discordia diagram for nine samples of the 3.56 billion-year-old Morton Gneiss, Minn. After Goldich and others (56).



Some Creationist Criticisms Of Radiometric Dating

“ANOMALOUS” AGES

The advocates of “scientific” creationism frequently point to apparent inconsistencies in radiometric dating results as evidence invalidating the techniques. This argument is specious and akin to concluding that all wristwatches do not work because you happen to find one that does not keep accurate time. In fact, the number of “wrong” ages amounts to only a few percent of the total, and nearly all of these are due to unrecognized geologic factors, to unintentional misapplication of the techniques, or to technical difficulties. Like any complex procedure, radiometric dating does not work all the time under all circumstances. Each technique works only under a particular set of geologic conditions and occasionally a method is inadvertently misapplied. In addition, scientists are continually learning, and some of the “errors” are not errors at all but simply results obtained in the continuing effort to explore and improve the methods and their application. There are, to be sure, inconsistencies, errors, and results that are poorly understood, but these are very few in comparison with 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.

Most of the “anomalous” ages cited by creation “scientists” in their attempt to discredit radiometric dating are actually misrepresentations of the data, commonly cited out of context and misinterpreted. A few examples will demonstrate that their criticisms are without merit.

The Woodmorappe List

The creationist author J. Woodmorappe (134) lists more than 300 supposedly "anomalous" radiometric ages that he has culled from the scientific literature. He claims that these examples cast serious doubt on the validity of radiometric dating.

> The use of radiometric dating in Geology involves a very selective acceptance of data. Discrepant dates, attributed to open systems, may instead be evidence against the validity of radiometric dating. (134, p. 102)

However, close examination of his examples, a few of which are listed in Table 2, shows that he misrepresents both the data and their meaning.

Table 2: Examples of Supposedly "Discrepant" Radiometric Ages, as Tabulated and Discussed by Woodmorappe (134)

*This example was not tabulated by Woodmorappe (134) but was discussed in his text.

Expected age (million years)	Age obtained (million years)	Formation/locality
52	39	Winona Sand/gulf coast
60	38	Not given/gulf coast
140	163,186	Coast Range batholith/Alaska
185	186-1230	Diabase dikes/Liberia
-	34,000*	Pahrump Group diabase/California

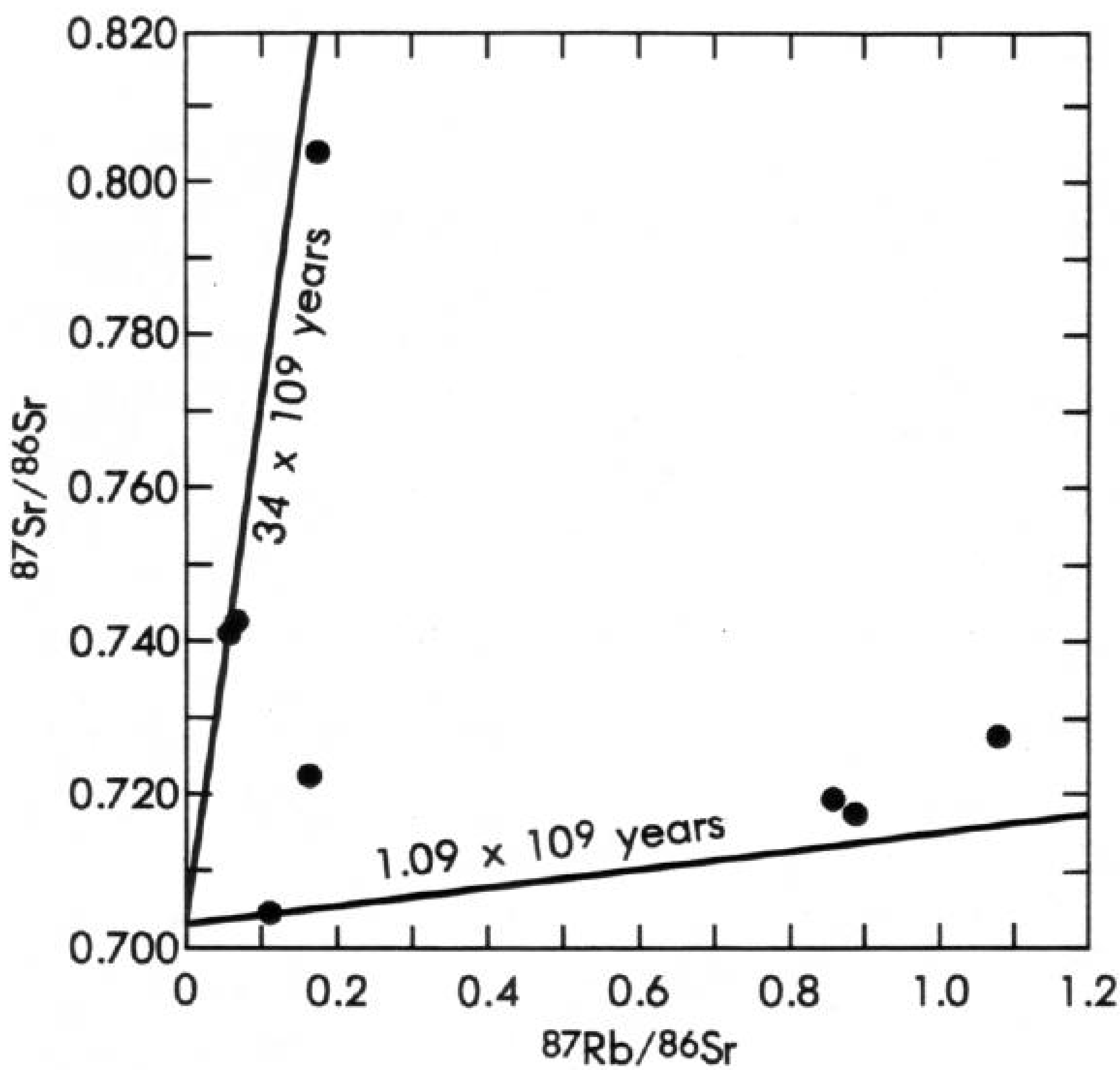
The two ages from gulf coast localities (Table 2) are from a report by Evernden and others (43). These are K-Ar data obtained on glauconite, a potassium-bearing clay mineral that forms in some marine sediment. Woodmorappe (134) fails to mention, however, that these data were obtained as part of a controlled experiment to test, on samples of known age, the applicability of the K-Ar method to glauconite and to illite, another clay mineral. He also neglects to mention that most of the 89 K-Ar ages reported in their study agree very well with the expected ages. Evernden and others (43) found that these clay minerals are extremely susceptible to argon loss when heated even slightly, such as occurs when sedimentary rocks are deeply buried. As a result, glauconite is used for dating only with extreme caution. Woodmorappe's gulf coast examples are, in fact, examples from a carefully designed experiment to test the validity of a new technique on an untried material.

The ages from the Coast Range batholith in Alaska (Table 2) are referenced by Woodmorappe (134) to a report by Lanphere and others (80). Whereas Lanphere and his colleagues referred to these two K-Ar ages of 163 and 186 million years, the ages are actually from another report and were obtained from samples collected at two localities in Canada, not Alaska. There is nothing wrong with these ages; they are consistent with the known geologic relations and represent the crystallization ages of the Canadian samples. Where Woodmorappe obtained his 140-million-year "expected" age is anyone's guess because it does not appear in the report he cites.

The Liberian example (Table 2) is from a report by Dalrymple and others (34). These authors studied dikes of basalt that intruded Precambrian crystalline basement rocks and Mesozoic sedimentary rocks in western Liberia. The dikes cutting the Precambrian basement gave K-Ar ages ranging from 186 to 1213 million years (Woodmorappe erroneously lists this higher age as 1230 million years), whereas those cutting the Mesozoic sedimentary rocks gave K-Ar ages of from 173 to 192 million years. $^{40}Ar/^{39}Ar$ experiments[4] on samples of the dikes showed that the dikes cutting the Precambrian basement contained excess ^{40}Ar and that the calculated ages of the dikes do not represent crystallization ages. The $^{40}Ar/^{39}Ar$ experiments on the dikes that intrude the Mesozoic sedimentary rocks, however, showed that the ages on these dikes were reliable. Woodmorappe (134) does not mention that the experiments in this study were designed such that the anomalous results were evident, the cause of the anomalous results was discovered, and the crystallization ages of the Liberian dikes were unambiguously determined. The Liberian study is, in fact, an excellent example of how geochronologists design experiments so that the results can be checked and verified.

The final example listed in Table 2 is a supposed 34 billion-year Rb-Sr isochron age on diabase of the Pahrump Group from Panamint Valley, California, and is referenced to a book by Faure and Powell (50). Again, Woodmorappe (134) badly misrepresents the facts. The "isochron" that Woodmorappe (134) refers to is shown in Figure 6 as it appears in Faure and Powell (50). The data do not fall on any straight line and do not, therefore, form an isochron. The original data are from a report by Wasserburg and others (130), who plotted the data as shown but did not draw a 34-billion-year isochron on the diagram. The "isochrons" lines were drawn by Faure and Powell (50) as "reference isochrons" solely for the purpose of showing the magnitude of the scatter in the data.

Figure 6: The Rb-Sr "isochron" from the diabase of the Pahrump Group, interpreted by Woodmorappe (134) as giving a radiometric age of 34 billion years. The lines are actually "reference" isochrons, drawn by Faure and Powell (50) to illustrate the extreme scatter of the data. This scatter shows clearly that the sample has been an open system and that its age cannot be determined from these data. Radiometric ages on related formations indicate that the Pahrump diabase is about 1.2 billion years old. Original data from Wasserburg and others (130).



As discussed above, one feature of the Rb-Sr isochron diagram is that, to a great extent, it is self-diagnostic. The scatter of the data in Figure 6 shows clearly that the sample has been an open system to ^{87}Sr (and perhaps to other isotopes as well) and that no meaningful Rb-Sr age can be calculated from these data. This conclusion was clearly stated by both Wasserburg and others (130) and by Faure and Powell (50). The interpretation that the data represent a 34 billion-year isochron is solely Woodmorappe's (134) and is patently wrong.

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. (77, p. 201)

There are two things wrong with this argument. First, the lead data that Kofahl and Segraves (77) cite, which come from a report by Oversby (102), are common lead measurements done primarily to obtain information on the genesis of the Reunion lavas and secondarily to estimate when the parent magma the lava was derived from was separated from primitive mantle material. These data cannot be used to calculate the age of the lava flows and no knowledgeable scientist would attempt to do so. Second, the U-Pb and Pb-Pb lava "ages" cited by Kofahl and Segraves do not appear in Oversby's report. 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 obtained their numbers.

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. (92, p. 147)

The data Morris (92) refers to were published by Evernden and others (44), but include samples from different islands that formed at different times! 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 (86, 87). The approximate age of 250,000 years was the mean of the results from four samples from the Island of Hawaii, which is much younger than Kauai. 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.

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. (117, p. 39, and similar statements in 92)

Slusher (117) and Morris (92) advanced this argument in an attempt to show that the K-Ar method is unreliable, but the argument is a red herring.

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 (36, 101). This effect is most serious in the rims of the pillows and increases in severity with water depth. The excess ^{40}Ar content 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 be unreliable. Such studies are not unusual because each different type of mineral and rock has to be tested carefully before it can be used for any radiometric dating technique. In the case of the submarine pillow basalts, the results clearly indicated that these rocks are unsuitable for dating, and so they are not generally used for this purpose except in special circumstances and unless there is some independent way of verifying the results.

"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. (77, p. 200)

The citation for this statement is to a report by Turner (128). Turner, however, made no such comment about excess argon in lunar rocks, and there are no data in his report on which such a conclusion could be based. The statement by Rofahl and Segraves (77) is simply unjustifiable.

The 1801 Flow from Hualalai 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. (77, p. 200)

Similar modern rocks formed in 1801 near Hualalai, Hawaii, were found to give potassium-argon ages ranging from 160 million years to 3 billion years. (92, p. 147)

Kofahl and Segraves (77) and Morris (92) cite a study by Funkhouser and Naughton (51) on xenolithic inclusions in the 1801 flow from Hualalai Volcano on the Island of Hawaii.

The 1801 flow is unusual 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 (51) was on the xenoliths, not on the lava. The xenoliths, which vary in composition and range in size from single mineral grains to rocks as big as 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 the K-Ar technique. 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 are routinely done to ascertain which materials are suitable for dating and which are not, and to determine the cause of sometimes strange results. They are part of a continuing effort to learn.

Two extensive K-Ar studies on historical lava flows from around the world (31, 79) showed that excess argon is not a serious problem for dating lava flows. The authors of these reports “dated” numerous lava flows whose age was known from historical records. In nearly every case, the measured K-Ar age was zero, as expected if excess argon is uncommon. An exception is the lava from the 1801 Hualalai flow, which is so badly contaminated by the xenoliths that it is impossible to obtain a completely inclusion-free sample.

METHODOLOGY

Creation “scientists” commonly criticize the systematics and methodology of radiometric dating, often implying in the process that scientists do not arrive at their conclusions honestly. One of the principal practitioners of this approach is Slusher (117), whose “Critique of Radiometric Dating” abounds with such unjustified statements. A few examples will illustrate that the comments by Slusher (117) and other creation “scientists” are based on ignorance of the methods and are unfounded.

Initial ^{87}Sr

There is really no valid way of determining what the initial amounts of Sr^{87} in rocks were. There is much juggling of numbers and equations to get results in agreement with the U-Th-Pb “clocks.” In all these radioactive clocks, all methods are made to give values that fit the evolutionist’s belief as to the age of the earth and the ages of the geological events. The reason that the various dating methods give similar ages after “analysis” is that they are made to do so. In the case of the initial Sr^{87}/Sr^{86} ratios, these values can be adjusted so that any age desired is obtainable. (117, p. 40)

Slusher (117) is wrong on all counts.

As discussed above in the section on Rb-Sr dating the simplest form of Rb-Sr dating (i.e., dating by measuring the ^{87}Rb and ^{87}Sr contents in a single sample) can be done only on those samples that are so low in initial ^{87}Sr that the initial Sr correction is negligible. Such samples are rare, and so nearly all modern Rb-Sr dating is done by the isochron method. The beauty of the Rb-Sr isochron method is that knowledge of the initial Sr isotopic composition is not necessary — it is one of the results obtained. Contrary to Slusher’s (117) statement, the amount of initial ^{87}Sr is not needed to solve the Rb-Sr isochron age equation, only the current $^{87}Sr/^{86}Sr$ ratio, and the initial $^{87}Sr/^{86}Sr$ ratio is not adjusted for any purpose.

A second advantage of the isochron method is that it contains internal checks on reliability. Look again at the isochron for the meteorite Juvinas (Figure 3). The initial $^{87}Sr/^{86}Sr$ ratio of 0.69896 was not assumed; it was a result of the isochron analysis. The data are straightforward (albeit technically complex) measurements that fall on a straight line, indicating that the meteorite has obeyed the closed-system requirement. The decay constants used in the calculations were the same as those in use throughout the world in

1975.[5] These data were not "made" to result in an old age, as Slusher (117) claims. The age of 4.60 ± 0.07 billion years is a result obtained because Juvinas is genuinely an ancient object.

Initial ^{40}Ar

There is far too much Ar^{40} in the earth for more than a small fraction of it to have been formed by radioactive decay of K^{40}. This is true even if the earth were really 4.5 billion years old. In the atmosphere of the earth, Ar^{40} constitutes 99.6% of the total argon. This is around 100 times the amount that would be generated by radioactive decay over the hypothetical 4.5 billion years. Certainly this is not produced by an influx from outer space. Thus it would seem that a large amount of Ar^{40} was present in the beginning. Since geochronologists assume that errors due to presence of initial Ar^{40} are small, their results are highly questionable. (117, p.39)

This statement contains several serious errors. First, there is not more ^{40}Ar in the atmosphere than can be accounted for by radioactive decay of ^{40}K over 4.5 billion years. An amount of ^{40}Ar equivalent to all the ^{40}Ar now in the atmosphere could be generated in 4.5 billion years if the Earth contained only 85 ppm potassium. Current estimates of the composition of the Earth indicate that the crust contains about 1.9 percent potassium and the mantle contains between 100 and 400 ppm potassium. The ^{40}Ar content of the atmosphere is well known and is 6.6×10^{19} grams. The estimated ^{40}Ar content of the crust and mantle combined is about 4 to 19×10^{19} grams (60). Thus, the Earth and the atmosphere now contain about equal amounts of ^{40}Ar, and the total could be generated if the Earth contained only 170 ppm potassium and released half of its ^{40}Ar to the atmosphere. Second, there have been sufficient tests to show that during their formation in the crust, igneous and metamorphic rocks nearly always release their entrapped ^{40}Ar, thus resetting the K-Ar clock. In addition, scientists typically design their experiments so that anomalous results, such as might be caused by the rare case of initial ^{40}Ar, are readily apparent. The study of the Liberian diabase dikes, discussed above, is a good example of this practice.

Isochrons

Several creation "scientists" have attempted to discredit Rb-Sr isochron dating by criticizing the fundamental principles of the method. Three of these criticisms are worth examining because they illustrate how little these creation "scientists" understand about the fundamentals of geochemistry in general and about isochrons in particular.

1. Uniform Initial $^{87}Sr/^{86}Sr$ Ratio

Now concerning the assumption that the samples had the same initial Sr^{87}/Sr^{86} ratio, some pertinent remarks may be made. First, if it is assumed that there is a uniform distribution of Sr^{87} in the rock, then it is assumed that there is also a uniform distribution of Rb^{87}. But, of course, this is not assumed by the geochronologist since there would, by conventional theory, have to be a clustering of his points at one position on a Sr^{87}/Sr^{86} vs. Rb^{87}/Sr^{86} graph. (117, p. 42)

There are two serious flaws in Slusher's (117) argument; first, the Rb-Sr isochron method does not require a uniform distribution of ^{87}Sr. It only requires that the Sr isotopic composition, i.e., the $^{87}Sr/^{86}Sr$ ratio, be constant in all phases (commonly minerals from the same rock) at the time the rock formed (Figure 2). Even though the various minerals will incorporate different amounts of Sr as they cool and form, the Sr isotopic composition will be the same because natural processes do not significantly fractionate isotopes with so little mass difference as ^{87}Sr and ^{86}Sr. Second, Slusher (117) has confused isotopes and elements. It would be absurd to assume that either the amount of ^{87}Rb or the $^{87}Rb/^{86}Sr$ ratio is uniform when a rock forms. Rb and Sr are quite different elements and are incorporated into the various minerals in varying proportions according to the composition and structure of the minerals. The Rb-Sr isochron method works precisely because the Rb/Sr ratio, expressed in the isochron diagram as $^{87}Rb/^{86}Sr$ (Figure 2), varies from mineral to mineral at formation, whereas the Sr isotopic composition ($^{87}Sr/^{86}Sr$ ratio) does not.

2. The $^{54}Fe/^{86}Sr$ Ratio Versus $^{58}Fe/^{86}Sr$ Ratio Analogy

Dr. Cook has pointed out that the obtaining of the isochrons is better explained as a natural isotopic variation effect, since similar curves are obtained for plots of Fe^{54}/Sr^{86} vs Fe^{58}/Sr^{86} which are known not to be time functions since these ratios have nothing to do with radioactivity because these isotopes are not radioactive. There is no way to correct for this natural isotopic variation since there is no way to determine it. This renders the Rb^{87}-Sr^{87} series useless as a clock. (117, p. 42)

Slusher (117) is wrong again. He has used an invalid analogy and come to an erroneous conclusion. ^{54}Fe and ^{58}Fe are naturally occurring isotopes of iron whose abundance is 5.8 and 0.3 percent, respectively, of the total iron. All a plot of $^{54}Fe/^{86}Sr$ ratio versus $^{58}Fe/^{86}Sr$ ratio demonstrates is that (1) the Fe/Sr ratio is not constant, and (2) the ^{54}Fe content increases with the ^{58}Fe content; both are expectable results. The slope of the line in such a plot is simply the natural abundance $^{54}Fe/^{58}Fe$ ratio. The same sort of line will be obtained by plotting any pair of naturally occurring isotopes of the same element normalized by any nonradiogenic isotope, including $^{87}Rb/^{86}Sr$ ratio versus $^{85}Rb/^{86}Sr$ ratio. Contrary to Slusher's (117) statement, these plots demonstrate only elemental variations in nature, not isotopic fractionation, and they have nothing to do with the validity of the Rb-Sr isochron.

The Rb-Sr isochron differs from Slusher's (117) analogy in a very important way; i.e., the $^{87}Sr/^{86}Sr$ ratio in a system, plotted on the ordinate (Figure 2), can only vary by radioactive decay of ^{87}Rb, plotted on the abscissa, over time. In comparing the Rb-Sr isochron diagram with Cook's Fe/Sr diagram, Slusher (117) is merely showing that he does not understand either.

3. Isochrons and Mixing Lines

Arndts and Overn (8) and Kramer and others (78) claim that Rb-Sr isochrons are the result of mixing, rather than of decay of ^{87}Rb over long periods:

> It is clear that mixing of pre-existent materials will yield a linear array of isotopic ratios. We need not assume that the isotopes, assumed to be daughter isotopes, were in fact produced in the rock by radioactive decay. Thus the assumption of immense ages has not been proven.
>
> The straight lines, which seem to make radiometric dating meaningful, are easily assumed to be the result of simple mixing. (8, p. 6)

These authors note that it is mathematically possible to form a straight line on a Rb-Sr isochron diagram by mixing, in various proportions, two end members of different $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ compositions.

A test sometimes employed to check for mixing is to plot the $^{87}Sr/^{86}Sr$ ratio against 1/Sr (49). This plot shows whether the $^{87}Sr/^{86}Sr$ ratio varies systematically with the Sr content of the various samples analyzed, as would be the case if the isochron were due to mixing rather than radioactive to decay over time. Kramer and others (78) have analyzed the data from 18 Rb-Sr isochrons published in the scientific literature by plotting the $^{87}Sr/^{86}Sr$ ratio versus 1/Sr and calculating the correlation coefficient (C.C.) to test for linear relations:

> We found that 8 (44%) had a C.C. in excess of .9; 5 additional (28%) had a C.C. in excess of .8; 1 additional (6%) had a C.C. in excess of .7; 2 additional (11%) had a C.C. in excess of .6; and 2 (11%) had a C.C. less than .5 …
>
> This preliminary study of the recent evolutionary literature would suggest that there are many published Rb-Sr isochrons with allegedly measured ages of hundreds of millions of years which easily meet the criteria for mixing, and are therefore more cogently indicative of recent origin. (78, p.2)

Whereas a linear plot on a diagram of $^{87}Sr/^{86}Sr$ versus 1/Sr is a necessary consequence of mixing, it is not a sufficient test for mixing. Kramer and others (78) and Arndts and Overn (8) have come to an incorrect conclusion because they have ignored several important facts about the geochemistry of Rb-Sr systems and the systematics of isochrons.

First, the chemical properties of rubidium and strontium are quite different, and thus their behavior in minerals is dissimilar. Both are trace elements and rarely form minerals of their own. Rubidium is an alkali metal, with a valence of +1 and an ionic radius of 1.48 Å. It is chemically similar to potassium and tends to substitute for that element in minerals in which potassium is a major constituent, such as potassium feldspar and the micas muscovite and biotite. Strontium, on the other hand, is an alkaline-earth element, with a valence of +2 and an ionic radius of 1.13 Å. It commonly substitutes for calcium in calcium minerals, such as the plagioclase feldspars. The chemical properties of rubidium and strontium are so dissimilar that minerals which readily accept rubidium into their crystal structure tend to exclude strontium and vice versa. Thus, rubidium and strontium in minerals tend to be inversely correlated; minerals high in rubidium are generally low in strontium and vice versa. Because minerals high in rubidium will also have higher $^{87}Sr/^{86}Sr$ ratios within a given period than those low in rubidium (see Figure 2), the $^{87}Sr/8^{6S}$ r ratio commonly is inversely correlated with the Sr content. Thus, mineral and rock isochron data will commonly show a quasi-linear relation on a diagram of 87Sr/86Sr versus 1/Sr, with the $^{87}Sr/^{86}Sr$ ratio increasing with increasing 1/Sr. This relation, however, is a natural consequence of the chemical behavior of rubidium and strontium in minerals and of the decay of ^{87}Rb to ^{87}Sr over time, and has nothing to do with mixing.

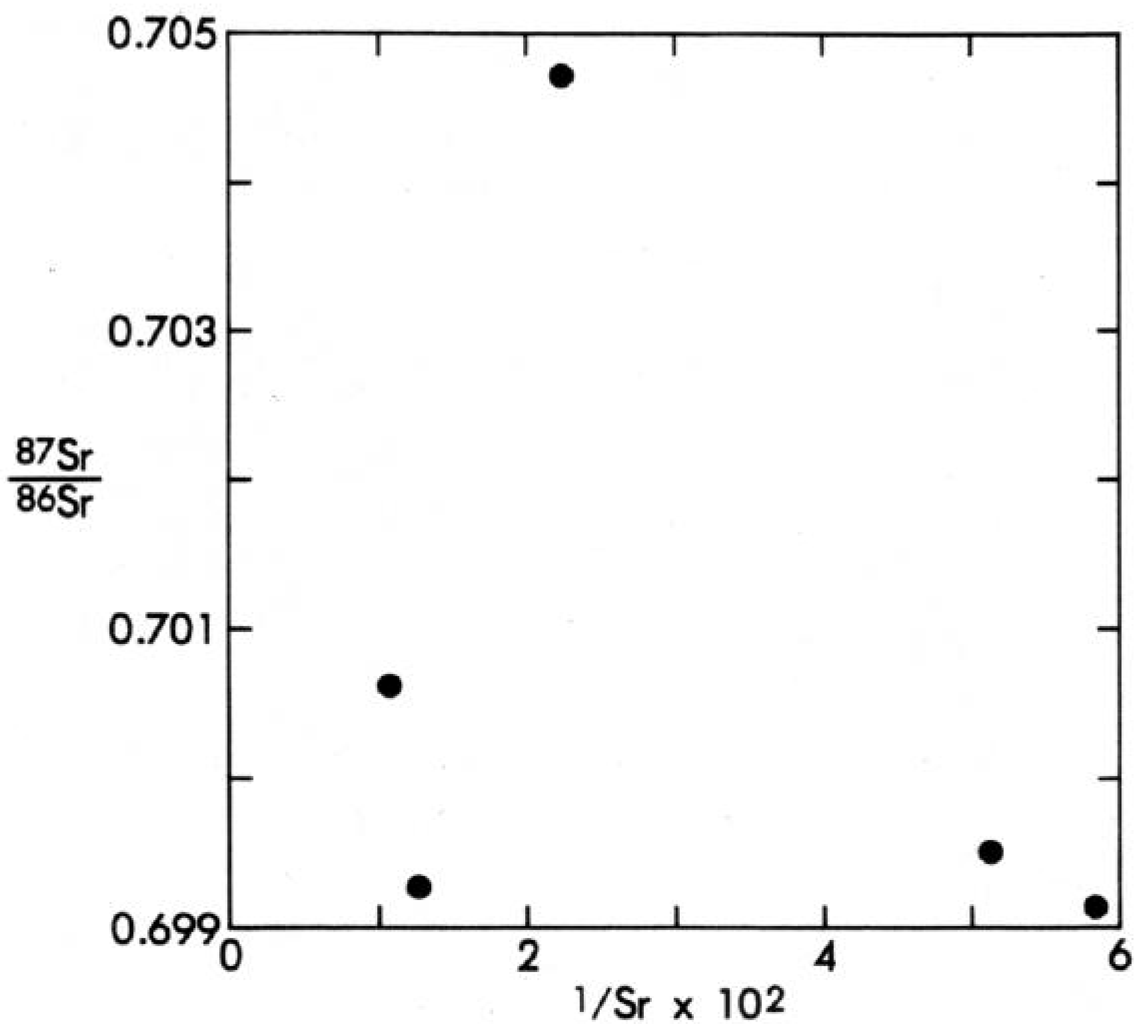
Second, mixing is a mechanical process that is physically possible only in those rock systems where two or more components with different chemical and isotopic compositions are available for mixing. Examples include the mingling of waters from two streams, the mixing of sediment from two different source rocks, and the contamination of lava from the mantle by interactions with the crustal rocks through which it travels to the surface. Mixing in such systems has been found (49, 70), but the Rb-Sr method is rarely used on these systems. The Rb-Sr isochron method is most commonly used on igneous rocks, which form by cooling from a liquid. Mineral composition and the sequence of mineral formation are governed by chemical laws and do not involve mixing. In addition, a rock melt does not contain isotopic end members that can be mechanically mixed in different proportions into the various minerals as they form, nor could such end members be preserved if they were injected into a melt.

Third, how could an end member with a high $^{87}Sr/^{86}Sr$ ratio exist if this ratio ultimately were not due to the decay of ^{87}Rb over time? Even if isochrons were the result of mixing — which they are not — the existence of a high $^{87}Sr/^{86}Sr$ ratio end member would indicate the passage of billions of years.

Fourth, if isochrons were the result of mixing, approximately half of them should have negative slopes. In fact, negative slopes are exceedingly rare and are confined to those types of systems, mentioned above, in which mechanical mixing is possible and evident.

Finally, there are numerous isochrons that do not show a positive correlation on a diagram of the $^{87}Sr/^{86}Sr$ versus 1/Sr. An example is the meteorite Juvinas (Figure 3). A plot of the $^{87}Sr/^{86}Sr$ ratio versus 1/Sr for this meteorite (Figure 7) shows clearly that there is no linear relation. Thus, even using the criteria developed by Arndts and Overn (8) and Kramer and others (78), the 4.6-billion-year isochron for Juvinas must be accepted as representing a valid crystallization age.

Figure 7: $^{87}Sr/^{86}Sr$ ratio versus 1/Sr for the meteorite Juvinas. The absence of a linear relation proves that the isochron shown in Figure 3 could not be due to mixing. Data from Allegre and others (3).



Therefore, arguments advance by Arndts and Overn (8) and by Kramer and others (78) are based on premises that are geochemically and logically unsound, and their conclusion that isochrons are due to mixing rather than to decay of ^{87}Rb over geologic time is incorrect.

Instrumentation

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. (117, p. 45)

This statement was as untrue when it was first written in 1973 (117, 1973 ed., p. 35) as it is today. Modern counting instruments, available for more than two decades, are capable of counting the ^{14}C activity 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

Creation "scientists" commonly claim that the process of radioactive decay is not constant. Before discussing some of their claims, it is worth discussing briefly the types of radioactive decay and the evidence that decay is constant over the range of conditions undergone by the rocks available to scientists.

Most radioactive decay involves the ejection of one or more sub-atomic particles from the nucleus. Alpha 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 decay involves the ejection of a beta particle (an electron) from the nucleus. Gamma 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 essentially unaffected by physical or chemical conditions. The reasons for this are that nuclear forces act over distances much smaller than the distances between nuclei, and that the amounts of energy involved in nuclear transformations are much greater than those involved in normal chemical reactions or normal physical conditions. Putting it another way, the "glue" holding the nucleus together is extremely effective, and the nucleus is well insulated from the external world by the electron cloud surrounding every atom. This combination of the strength of nuclear binding and the insulation of the nucleus 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 experiments have invariably failed to produce any 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. Measurements of decay rates under differing gravitational and magnetic fields also have yielded negative results. Although changes in alpha and beta decay rates are theoretically possible, theory also predicts that such changes would be very small (42) and thus would not affect dating methods. Under certain environmental conditions, the decay characteristics of ^{14}C, ^{60}Co, and ^{137}Ce, all of which decay by beta emission, do deviate slightly from the ideal random distribution predicted by current theory (5, 6), but changes in the decay constants have not been detected.

There is a fourth type of decay that can be affected by physical and chemical conditions, though only very slightly. This type of decay is electron capture (e.c. or K-capture), in which an orbital electron is captured by the nucleus and a proton is converted into a neutron. Because this type of decay involves a particle outside 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 different beryllium chemical compounds varies by as much as 0.18 percent (42, 64,). The only isotope of geologic interest that undergoes e.c. decay 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 various conditions indicate that variations in the chemical and physical environment have no detectable effect on its e.c. decay constant.

Another type of decay for which small changes in rate have been observed is internal conversion (IC). During i nternal conversion, however, an atom's nucleus goes from one energy state to a lower energy state; it does not involve any elemental transmutation and is, therefore, of little relevance to radiometric dating methods.

Slusher (115, 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 or e.c. decays with exceedingly small changes in rates. For example, in the first (1973) edition of his monograph on radiometric dating, Slusher (117) claims that the decay rate of ^{57}Fe has been changed by as much as 3 percent by electric fields; however this is an IC decay, and ^{57}Fe remains Fe. Note, however, that even a 3 percent 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. DeYoung (37) lists 20 isotopes whose decay rates have been changed by environmental conditions, alluding to the possible significance of these changes to geochronology, but the only significant changes are for isotopes that “decay” by internal conversion. These changes are irrelevant to radiometric dating methods.

Morris (92) claims that free neutrons might change decay rates, but his arguments show that he does not understand either neutron reactions or radioactive decay. Neutron reactions do not change decay rates but, instead, transmute one nuclide into another. The result of the reaction depends on the properties of the target isotope and on the energy of the penetrating neutron. There are no neutron reactions that produce the same result as either beta or alpha decay. An (n,p) (neutron in, proton out) reaction produces the same change in the nucleus of an atom as e.c. 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 measurable nuclear transformations in common elements that would clearly indicate the occurrence of such a process. No such transformations have been found, and so Morris’ claims are disproved.

Morris (92) also suggests that neutrinos might change decay rates, citing a column by Jueneman (72) 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 “re-set” all the radiometric clocks. Jueneman describes a highly speculative hypothesis that would account 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. Jueneman, however, does not propose that decay rates would be changed, nor does he state how the clocks would be reset; in addition, there is no evidence to support his speculation. Neutrinos are particles that are emitted during beta decay. They have no charge and very small or possibly no rest mass. Their existence was proposed by Wolfgang 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 interact much with matter — most pass unimpeded right through the Earth — and they can be detected experimentally only with great difficulty. The chance that neutrinos could have any effect on decay rates or produce nuclear transmutations in sufficient amounts to have any significant effect on our radiometric clocks is exceedingly small.

Slusher (117) and Rybka (110) also propose that neutrinos can change decay rates, citing an hypothesis by Dudley (40) that decay is triggered by neutrinos in a “ neutrino sea” and that changes in the neutrino flux might affect decay rates. This argument has been refuted by Brush (20), who points out that Dudley’s hypothesis not only requires rejection of both relativity and quantum mechanics, two of the most spectacularly successful theories in modern science, but is disproved by recent experiments. Dudley himself rejects the conclusions drawn from his hypothesis by Slusher (117) and Rybka (110), noting that the observed changes in decay rates are insufficient to change the age of the Earth by more than a few percent (Dudley, personal communication, 1981, quoted in 20, p. 51). Thus, even if Slusher and Rybka were correct — which they are not — the measured age of the Earth would still exceed 4 billion years.

Slusher (115, 117) and Rybka (110) also claim that the evidence from pleochroic halos[6] indicates that decay rates have not been constant over time:

> … evolutionist geologists have long ignored the evidence of variability in the radii of pleochroic halos, which shows that the decay rates are not constant and would, thus, deny that some radioactive elements such as uranium could be clocks. (115, p. 283)

In a review of the subject, however, Gentry (52) concludes that the data from pleochroic halo studies are inconclusive on this point — the uncertainties in the measurements and other factors are too great.

Rybka (110) claims that experimental evidence suggests that decay rates have changed over time:

> Two cases where it appears that the half life is increasing with time are as follows. Glasstone (1950) has the half life for Protactinium 231 as 3.2×10^4 years while Kaplan (1962) has the half life as 3.43×10^4 years. For the half life of Radium 223, Glasstone has 11.2 days while Kaplan has 11.68 days. (110, p. ii)

Rybka’s (110) analysis of the situation, however, is wrong. He has failed to consider all of the data.

The various values for the half lives of ^{223}Ra and ^{231}Pa reported in the literature since 1918 are given in Table 3. It is clear that there is no increase in the values as a function of time. The differences in the reported half lives are a consequence of improved methods and instruments, and the care with which the individual measurements were made. For example, Kirby and others (74) argue convincingly that the measurements of the half life of ^{223}Ra reported from 1953 to 1959 (Table 3) suffered from inadequate experimental methods and are not definitive. Kirby and his colleagues carefully measured this half life by two different methods and obtained values of 11.4347 ± 0.0011 days and 11.4267 ± 0.0062 days. The weighted mean of these two measurements is 11.4346 ± 0.0011 days, which currently is the best value for the half life of ^{223}Ra. I should also mention that the two references cited by Rybka are textbooks, not the publications in which the original data were reported; the dates of publication of these texts, therefore, do not reflect the years in which the measurements were made or reported.

Table 3: Measurements of the Half-lives of 223Ra and 231Pa. Data from Lederer and Shirley (81), Kirby et al. (74), and references therein

Nuclide	Year Reported	Half-Life
^{223}Ra	1918	11.2 days
	1953	11.1 days
	1954	11.685 days
	1959	11.22 days
	1959	11.41 days
	1965	11.4346 days
^{231}Pa	1930	3.2×10^4 years
	1932	3.2×10^4 years
	1949	3.43×10^4 years
	1968	3.234×10^4 years
	1969	3.276×10^4 years
	1977	3.276×10^4 years

Rybka (110) also explores the consequences of a hypothetical change over time of the decay constant, but his results are due solely to his arbitrary changes in the decay formula — changes for which there is neither a theoretical basis nor a shred of physical evidence.

In summary, the attempts by creation "scientists" to attack the reliability of radiometric dating by invoking changes in decay rates are meritless. There have been no changes observed in the decay constants of those isotopes used for dating, and the changes induced in the decay rates of other radioactive isotopes are negligible. These observations are consistent with theory, which predicts that such changes should be very small. Any inaccuracies in radiometric dating due to changes in decay rates can amount to, at most, a few percent.

ACCURACY OF CONSTANTS

Several creationist authors have criticized the reliability of radiometric dating by claiming that some of the decay constants, particularly those for ^{40}K, are not well known (28, 29, 92, 117). A common assertion is that these constants are "juggled" to bring results into agreement; for example:

> The so-called "branching ratio", which determines the amount of the decay product that becomes argon (instead of calcium) is unknown by a factor of up to 50 percent. Since the decay rate is also unsettled, values of these constants are chosen which bring potassium dates into as close correlation with uranium dates as possible. (92, p. 145)

There seems to be some difficulty in determining the decay constants for the K^{40}-Ar^{40} system. Geochronologists use the branching ratio as a semi-empirical, adjustable constant which they manipulate instead of using an accurate half-life for K^{40}. (117, p. 40)

These statements would have been true in the 1940s and early 1950s, when the K-Ar method was first being tested, but they were not true when Morris (92) and Slusher (117) wrote them. By the mid- to late 1950s the decay constants and branching ratio of ^{40}K were known to within a few percent from direct laboratory counting experiments (2). Today, all the constants for the isotopes used in radiometric dating are known to better than 1 percent. Morris (92) and Slusher (117) have selected obsolete information out of old literature and tried to represent it as the current state of knowledge.

In spite of the claims by Cook (28, 29), Morris (92), Slusher (115, 117), DeYoung (37) and Rybka (110), neither decay rates nor abundance constants are a significant source of error in any of the principal radiometric dating methods. The reader can easily satisfy himself on this point by reading the report by Steiger and Jaeger (124) and the references cited therein.

NEUTRON REACTIONS AND Pb-ISOTOPIC RATIOS

Neutron reaction corrections in the U-Th-Pb series reduce "ages" of billions of years to a few thousand years because most of the Pb can be attributed to neutron reactions rather than to radioactive decay. (117, p. 54)

Statements similar to this one by Slusher (117) are also made by Morris (92). These statements spring from an argument developed by Cook (28) that involves the use of incorrect assumptions and nonexistent data.

Cook's (28) argument, repeated in some detail by Morris (92) and Slusher (117), is based on U and Pb isotopic measurements made in the late 1930s and early 1950s on uranium ore samples from Shinkolobwe, Katanga and Martin Lake, Canada. Here, I use the Katanga example to show the fatal errors in Cook's (28) proposition.

Table 4: Uranium, Thorium, and Lead Analyses on a Sample (Nier 2) of Uranium Ore from Shinkolobwe, Katanga, as Reported by Faul (46). Data from Nier (100)

$^{206}Pb/^{238}U$ age = 616 million years

$^{206}Pb/^{207}Pb$ age = 610 million years

Element (weight percent in ore)	**Pb isotopes (percent of total Pb)**
U = 74.9	^{204}Pb = -----
Pb = 6.7	^{206}Pb = 94.25
Th = ---	^{207}Pb = 5.70
	^{208}Pb = 0.042

In the late 1930s, Nier (100) published Pb isotopic analyses on 21 samples of uranium ore from 14 localities in Africa, Europe, India, and North America and calculated simple U-Pb ages for these samples. Some of these data were later compiled in the book by Faul (46) that Cook (28) cites as the source of his data. Table 4 lists the data for one typical sample. Cook notes the apparent absence of thorium and ^{204}Pb, and the presence of ^{208}Pb. He reasons that the ^{208}Pb could not have come from the decay of ^{232}Th because thorium is absent, and could not be common lead because ^{204}Pb, which is present in all common lead, is absent. He reasons that the ^{208}Pb in these samples could only have originated by neutron reactions with ^{207}Pb and that ^{207}Pb, therefore, would also be created from Pb-206 by similar reactions:

$$^{206}Pb \xrightarrow{(n,\gamma)} {}^{207}Pb \xrightarrow{(n,\gamma)} {}^{208}Pb$$

Cook (28) then proposes that these effects require corrections to the measured lead isotopic ratios as follows: (1) the ^{206}Pb lost by conve rsion to ^{207}Pb must be added back to the ^{206}Pb; (2) the ^{207}Pb lost by conversion to ^{208}Pb must be added back to the ^{207}Pb; and (3) the ^{207}Pb gained by conversion from ^{206}Pb must be subtracted from the ^{207}Pb. He presents an equation for making these corrections:

$$\left(\frac{^{206}Pb}{^{207}Pb}\right)_c = \frac{^{206}Pb + {}^{208}Pb \times \left(\frac{^{206}Pb}{^{207}Pb}\right)}{^{207}Pb + {}^{208}Pb - {}^{208}Pb \times \left(\frac{^{206}Pb}{^{207}Pb}\right)}$$

based on the assumption that the neutron-capture cross sections[7] for ^{206}Pb and ^{207}Pb are equal, an assumption that Cook (28) calls "reasonable." Cook then substitutes the average values (which differ slightly from the values listed in Table 4) for the Katanga analyses into his equation and calculates a corrected ratio[8]:

$$\left(\frac{^{206}Pb}{^{207}Pb}\right)_c = \frac{94.2 + 0.08 \times \left(\frac{94.2}{5.7}\right)}{5.7 + 0.08 - 0.08 \times \left(\frac{94.2}{5.7}\right)} = 21.1$$

This calculation is repeated by both Morris (92) and Slusher (117). Cook (28), Morris (92), and Slusher (117) all note that this ratio is close to the present day production ratio of ^{206}Pb and ^{207}Pb from ^{238}U and ^{235}U, respectively, and conclude, therefore, that the Katanga ores are very young, not old. For example, Slusher (117) states:

> This corrected ratio says the corrected age should be practically zero since Pb^{206}/Pb^{207} = 21.5 for modern radiogenic lead. (117, p. 36)

Although Cook's (28) logic may, superficially, seem reasonable and straightforward, it suffers from several serious fundamental flaws. First, ^{204}Pb is not absent in the Katanga samples; it simply was not measured! In his report, Nier (100) states:

> 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. (100, p. 156)

Apparently, neither Cook (28), Morris (92), nor Slusher (117) bothered to read Nier's (100) complete report and erroneously interpreted the dash for ^{204}Pb in Faul's (46) tabulation as "zero," when, in fact, it means "not measured."

Second, the neutron-capture cross sections for ^{206}Pb and ^{207}Pb are not equal, as Cook (28) assumes, but differ by a factor of 24 (0.03 barns for ^{206}Pb, 0.72 barns for ^{207}Pb[‡]). This discrepancy has a significant effect on the results of Cook's (28) calculation. Table 5 compares the results of the three methods of age calculation — the correct method, Cook 's (28) method, and Cook's method with the correct nuclear cross sections — using the currently accepted best values for the uranium decay rate and abundance constants. The correct radiometric age is, of course, the scientific value of 622 million years. When Cook's (28) calculation is done with appropriate allowance for the unequal neutron-capture cross sections of ^{206}Pb and ^{207}Pb, the resulting calculated age is actually older than the scientific value, so even if such neutron reactions had occurred, the effect would be the opposite of that claimed by Cook (28). Note also that even Cook's (28) incorrect calculation results in an age of 70 million years, not "practically zero" as asserted by Slusher (117).

Table 5: Comparison of 206Pb/207Pb Age Calculations for the Katanga Uranium Ores, Using the Average Values from Cook (28) and the Modern Decay Rates and Abundance Constants

Method	$^{206}Pb/^{207}Pb$	Age (million years)
Scientific	16.53	622
Cook (28)	21.1	70
Cook's (28) calculation done correctly[†]	16.38	644

The third problem with Cook's proposition is that there are far too few free neutrons available in nature, even in uranium ores, to cause significant effects. This fact is readily acknowledged by Cook:

> In spite of evidence that the neutron flux is only a millionth as large as it should be to account for appreciable (n,) effects, there are several well documented examples that seem to demonstrate the reality of this scheme. (28, p. 54)

The examples are, of course, those from Katanga and Martin Lake.

Thus Cook's (28) proposition and calculations, enthusiastically endorsed by Morris (92) and Slusher (117), are based on data that do not exist and are, in addition, fatally flawed by demonstrably false assumptions. [1] An isolated system is one in which neither matter nor energy enters or leaves. A closed system is one in which only matter neither enters nor 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.

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

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

[4] The $^{40}Ar/^{39}Ar$ technique is an analytical variation of K-Ar dating. The validity of ages obtained by this technique can be verified from the data alone in a manner analogous to the Rb-Sr isochron method discussed above. For more information on $^{40}Ar/^{39}Ar$ dating, see Dalrymple (32).

[5] Improved constants were adopted worldwide in 1976 (124).

[6] Pleochroic halos are rings of discolored areas around radioactive inclusions in some minerals. The discoloration is caused by radiation damage to the crystals by subatomic particles. The radii of these rings are proportional to the energies of the particles.

[7] A nuclear reaction cross section, expressed in units of area (barns), is simply a measurement of the probability that the particle in question will penetrate the nucleus of the target isotope and cause the reaction in question.

[8] The values and equation actually give a result of 21.3. Cook published a result of 21.1. I have used Cook's result for consistency.

[‡] Note by Jon Fleming, 2005: Dalrymple does not provide a reference for his cross section values. They are not significantly different from modern values, such as the 26.6±1.2 mb for ^{206}Pb and 610±30 mb for ^{207}Pb reported in J. C. Blackmon, S. Raman, J. K. Dickens, R. M. Lindstrom, R. L. Paul, J. E. Lynn, "Thermal-neutron capture by ^{208}Pb", Physical Review C v65 #4 045801 (2002). Abstract (including the quoted numbers) at http://link.aps.org/abstract/PRC/v65/e045801, accessed December 6, 2005.

[†] Note by Jon Fleming, 2005: Dalrymple does not present the details of his derivation. See "Addendum: Derivation of the Neutron Reaction Correction Equation" for the derivation of the equation to which Dalrymple refers.

Scientific Age Of The Earth

Before analyzing the arguments advanced by creation "scientists" for a very young Earth, I here summarize briefly the evidence that has convinced scientists that the Earth is 4.5 to 4.6 billion years old.

There can be no doubt about the Earth's antiquity; the evidence is abundant, conclusive, and readily available to all who care to examine it. The best evidence is contained in the Earth's incomplete and complex but accurate stratigraphic record — a record that has been the subject of nearly two centuries of study. Slowly and painstakingly, geologists have assembled this record into the generalized geologic time scale shown in Figure 1. This was done by observing the relative age sequence of rock units in a given area and determining, from stratigraphic relations, which rock units are younger, which are older, and what assemblages of fossils are contained in each unit. Using fossils to correlate from area to area, geologists have been able to work out a relative worldwide order of rock formations and to divide the rock record and geologic time into the eras, periods, and epochs shown in Figure 1. The last modification to the geologic time scale of Figure 1 was in the 1930s, before radiometric dating was fully developed, when the Oligocene Epoch was inserted between the Eocene and the Miocene.

Although early stratigraphers could determine the relative order of rock units and fossils, they could only estimate the lengths of time involved by observing the rates of present geologic processes and comparing the rocks produced by those processes with those preserved in the stratigraphic record. With the development of modern radiometric dating methods in the late 1940s and 1950s, it was possible for the first time not only to measure the lengths of the eras, periods, and epochs but also to check the relative order of these geologic time units. Radiometric dating verified that the relative time scale determined by stratigraphers and paleontologists (Figure 1) is absolutely correct, a result that could only have been obtained if both the relative time scale and radiometric dating methods were correct.

The abundance and variety of fossils in Phanerozoic rocks have allowed geologists to decipher in considerable detail the past 600 million years or so of the Earth's history. In Precambrian rocks, however, fossils are rare; thus, the geologic record of this important part of the Earth's history has been especially difficult to decipher. Nonetheless, stratigraphy and radiometric dating of Precambrian rocks have clearly demonstrated that the history of the Earth extends billions of years into the past.

Radiometric dating has not been applied to just a few selected rocks from the geologic record. Literally many tens of thousands of radiometric age measurements are documented in the scientific literature. Since beginning operation in the early 1960s, the Geochronology laboratories of the U. S. Geological Survey in Menlo Park, California, have alone produced more than 20,000 K-Ar, Rb-Sr, and ^{14}C ages. Add to this number the age measurements made by from 50 to 100 other laboratories worldwide, and it is easy to see that the number of radiometric ages produced over the past two to three decades and published in the scientific literature must easily exceed 100,000. Taken as a whole, these data clearly prove that the Earth's history extends backward from the present to at least 3.8 billion years into the past.

A particularly fascinating question about the history of the Earth is "When did the Earth begin?" The answer to this question was provided by radiometric dating and is now known to within a few percent.

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. These oldest rocks are metamorphic rocks with earlier but now erased histories, so the ages obtained in this way are minimum ages for the Earth. Because 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 so intense nor so complex histories as the oldest Earth rocks, and they commonly record events nearer or 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, the other planets, and the Solar System, is to determine model lead ages for the Earth, the Moon, and meteorites. This method is thought to represent the time when lead isotopes were last homogeneously distributed throughout the Solar System and, thus, the time that the planetary bodies were segregated into discrete chemical systems. The results from these methods indicate that the Earth, meteorites, the Moon, and, by inference, the entire Solar System are 4.5 to 4.6 billion years old.

Before reviewing briefly the evidence for the age of the Earth, I emphasize that the formation of the Solar System and the Earth was not an instantaneous event but occurred over a finite period as a result of processes set in motion when the universe formed. It is, therefore, more correct to talk about formational intervals rather than discrete ages for the Solar System and the Earth. Present evidence indicates, however, that these intervals were rather short (100-200 million years) in comparison with the length of time that has elapsed since the Solar System formed some 4 to 5 billion years ago. Thus, the ages of the Earth, the Moon, and meteorites as measured by different methods represent slightly different events, although the differences in these ages are generally slight, and so, for the purposes of this chapter they are here treated as a single event.

THE EARTH'S OLDEST ROCKS

All 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, meaning 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 metamorphism and have had very complex histories. A metamorphic event may change the apparent radiometric age of a rock. Most commonly, the event causes partial or total loss of the radiogenic daughter isotope, resulting in a reduced age. Not all metamorphisms completely erase the radiometric record of a rock's age, although 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. Moreover, many of the oldest dated rocks intrude still older but undatable rocks. In all cases, the measured 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 (Figure 5). 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, have been dated by five different methods (Table 6); within the analytical uncertainties, the ages are the same and indicate that these rocks are about 3.7 billion years old.

Table 6: Radiometric Ages on the Amitsoq Gneisses, Western Greenland. Data from Baadsgaard (10), Moorbath et al. (89), Pettingill and Patchett (106)

weighted mean age 3.67 ± 0.06

Method	Age (billion years)
Rb - Sr isochron	3.70 ± 0.14
Lu - Hf isochron	3.55 ± 0.22
Pb - Pb isochron	3.80 ± 0.12
U - Pb discordia	3.65 ± 0.05
Th - Pb discordia	3.65 ± 0.08

Whole-rock samples from the Sand River Gneisses in the Limpopo Valley, South Africa, have been dated by the Rb-Sr isochron method at 3.79 ± 0.06 billion years (15). These samples are from rocks that contain inclusions of still older but as yet undatable rocks. Recently, Basu and others (16) 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 also indicates that there was a substantial period of history of the Earth before 3.8 billion years ago for which no datable geological record now exists. There are several possible reasons for the apparent absence of this earliest record. One reason is that during that period of Earth's history not only was the first continental crust forming, but it was also being vigorously recycled and regenerated. A second reason is that the Moon and, by inference, the Earth, were subjected to intense bombardment by large meteorites from the time of their initial formation to about 3.8 billion years ago; this bombardment occurred because the Earth was still sweeping up material in its orbital path. A third reason may be that the record of the Earth's early history exists somewhere but simply has not yet been found. The correct reason for the absence of data may well be some combination of the above. Whatever the reasons, if we are to learn more about the Earth's history before 3.8 billion years ago, we must examine the evidence obtained from other, older sources, particularly meteorites and the Moon.

AGES OF METEORITES

There are two basic types of meteorites, stone and iron; other types are intermediate in composition between these two. Stone meteorites are composed primarily of the silicate minerals olivine and pyroxene, whereas iron meteorites consist primarily of nickel-iron alloy. Stone meteorites commonly contain small amounts of nickel-iron, and many iron meteorites 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 meteorites are samples of the parent bodies that apparently were large enough to undergo partial melting and differentiation to produce different rock types. Others, primarily the stone meteorites called chondrites, seem to represent rocks essentially unchanged since condensation from the solar nebula. The orbits of meteorites indicate that they are parts of the Solar System, probably samples of the asteroids, and thus that 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. To determine the age of the Solar System and the Earth, we must search for the oldest, least disturbed meteorites.

K-Ar ages on stone meteorites 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, whereas the older ages record events near or equal to the time of meteorite formation. Many meteorites have now been dated by the $^{40}Ar/^{39}Ar$ age-spectrum method, which reveals that many meteorites were heated after their formation. The metallic phases in iron meteorites cannot be dated reliably by the K-Ar method because of their nearly negligible potassium content and cosmic-ray effects. However, silicate inclusions in several iron meteorites have been dated by the K-Ar method at 4.5 ± 0.2 billion years (19).

Some of the most precise ages on meteorites have been obtained by the Rb-Sr isochron method. Table 7 lists some of these ages, from Faure's (49) summary. Figure 3 plots the isochron for the meteorite Juvinas. Some iron meteorites containing small silicate inclusions have also been dated by the Rb-Sr isochron method; the results indicate that the least disturbed iron meteorites are of the same age (4.6 billion years) as the least disturbed stone meteorites.

Table 7: Summary of Some Rb-Sr Isochron Ages of Meteorites From the Compilation of Faure (49)

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

Material	Method	Age (billion years)
Juvinas (achrondrite)	Mineral isochron	4.60 ± 0.07
Allende (carbonaceous chrondrite)	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 ± 0.1
Krahenberg (amphoterite)	Mineral isochron	4.70 ± 0.01
Norton County (achondrite)	Mineral isochron	4.7 ± 0.1

Meteorites have also been dated by the Sm-Nd isochron method. Jacobsen and Wasserburg (69), for example, showed that 10 chondrites and the achondrite Juvinas all fall on an isochron of 4.60 billion years.

The results of radiometric dating on meteorites clearly indicate that these objects formed about 4.6 billion years ago. Because 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 no less than 4.6 billion years old.

AGES OF LUNAR ROCKS

The Apollo missions, for the first time, gave scientists the exciting opportunity to study samples from another planet. Although all the samples provide 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 the 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 particularly useful in the study of lunar rock formation because it tends to date 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; Table 8 lists some of these ages. As can be seen from this table, the rocks from each landing site give similar ages by both methods; this agreement cannot be a mere coincidence but must reflect the true ages of the rocks within the analytical uncertainties. Table 8, however, lists only data obtained before 1974; since that time, older rocks, from the lunar highlands, have been analyzed.

Numerous $^{40}Ar/^{39}Ar$ age-spectrum ages of highland rocks fall between about 4.0 and 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 ± 0.1, 4.60 ± 0.1, and 4.43 ± 0.05 billion years for three 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 in 75), and Sm-Nd isochron ages of 4.23 ± 0.05 and 4.34 ± 0.05 billion years have been determined for two Apollo 17 samples (23).

Table 8: Summary of Some Radiometric Ages of Lunar Basalts. From the Compilation by Head (62)

Location	Age (billion years)	Rock type	Sample	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

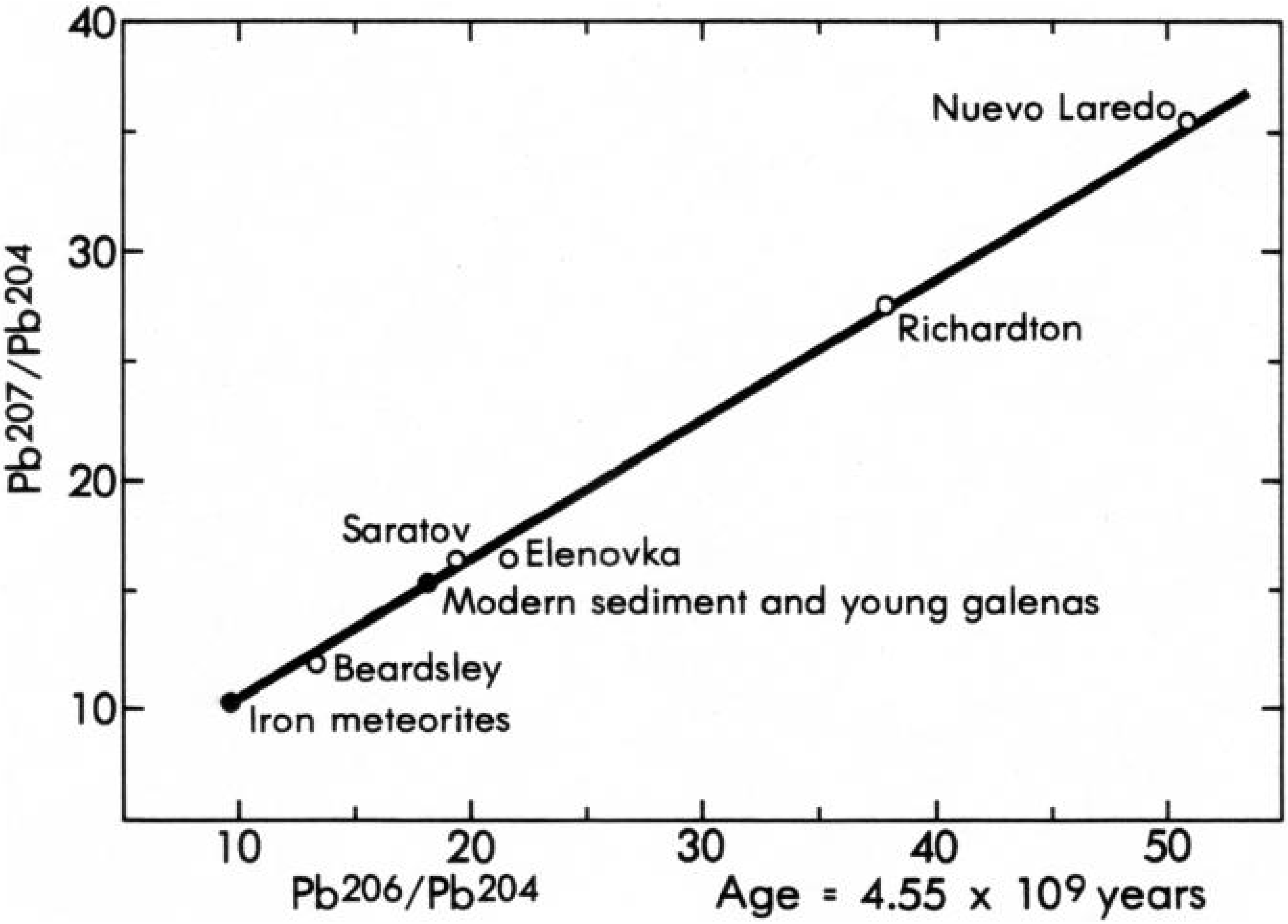
3.27	Quartz basalt	12051	^{40}Ar-^{39}Ar
3.26	Quartz basalt	12051	Rb-Sr
3.24	Olivine basalt	12002	^{40}Ar-^{39}Ar
3.24	Quartz basalt	12065	^{40}Ar-^{39}Ar
3.18	Quartz basalt	12064	Rb-Sr
3.16	Quartz basalt	12065	Rb-Sr

The hundreds of radiometric ages on lunar rocks show clearly that the initial formation of the Moon was 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 date of the major volcanic events that produced the igneous rocks at the various Apollo sites.

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 (65) and Holmes (63), and first applied to meteorites and the Earth by Clair Patterson, now at the California Institute of Technology, in 1953. In his classic paper, Patterson (104) reasoned that if the Pb-isotopic composition were uniform in the solar nebula and, thus, uniform in the planetary bodies and meteorites at the time of their formation, and if these bodies contained differing amounts of uranium, then the Pb-isotopic composition of these bodies should fall on a straight-line isochron when the ^{207}Pb/^{204}Pb ratio is plotted against the ^{206}Pb/^{204}Pb ratio (Figure 8). The lower end of the isochron in Figure 8 represents the Pb-isotopic composition in a phase of iron meteorites (troilite, or iron sulfide) that contains no uranium; this point represents the initial Pb-isotopic composition of the Solar System.

Figure 8: Meteoric lead-isotope isochron showing that the age of meteorites and the Earth is about 4.55 billion years. After Murthy and Patterson (98) and York and Farquhart (136).



The Pb-isotopic compositions of iron and stone meteorites fall on an isochron age of 4.55 billion years (Figure 8). Note that this method, like the other isochron methods, is self-checking. Modern Earth leads, as represented by the Pb-isotopic compositions of some very young non-uranium-bearing minerals, also fall close to the meteoritic isochron,[9] a result that we would expect if the Earth and meteorites formed contemporaneously. The ratios in lunar rocks have much larger values than those in terrestrial rocks and meteorites; they fall out of the field of Figure 8, but they do lie very close to the extension of the meteoritic isochron and, therefore, indicate a similar age.

If the Earth, the Moon, and meteorites were not genetically related and of the same age, there would be no reason for their Pb-isotopic 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. Note that Patterson's (104) original estimate of the age of the Earth has changed very little over the past three decades. In a recent reevaluation, Tera (125) concludes that the age of the Earth is about 4.54 billion years. Tera also summarizes several other lead models for the Earth's age; they all give results within the range 4.43 to 4.59 billion years. Thus, although there is still some debate about the exact age of the Earth and the 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, i.e., about two percent.[9] Although modern Earth leads lie near the meteoritic isochron, many do not fall exactly on it, evidently because many have had complex (multistage) histories (e.g., 123).

Some Creationist Ages Of The Earth

Other Links:

How Good Are Those Young-Earth Arguments?
A look at the arguments used by Kent Hovind to "prove" that the Earth is young.

An Index to Creationist Claims

A comprehensive look at the claims of all kinds of creationists arguments including young-earth arguments not debunked in "How Old is the Earth."

In spite of conclusive evidence of the Earth's antiquity, the proponents of "scientific" creationism stubbornly maintain that the Earth is only about 10,000 years old (Table 9). How do they arrive at these numbers? They have no consistent set of data that leads to any definite age for the Earth. Their "evidence" consists of invalid criticisms of the legitimate scientific data, as discussed above, and of some calculations that supposedly show that the Earth is very young. These calculations occur throughout the literature of creation "science" (e.g., 13, 77, 92, 116, 135), and they have been conveniently tabulated by Morris (93, 95) and Morris and Parker (97) (Table 10).

Concerning this tabulation, Morris and Parker (97) make the following statement:

There are, as a matter of fact, scores of worldwide processes which give ages far too young to suit the standard Evolution Model. There are 68 types of such calculations listed in Table I, all of them independent of each other and all applying essentially to the entire earth, or one of its major components or to the solar system. All give ages far too young to accommodate the Evolution Model. All are based on the same types of calculations and assumptions used by evolutionists on the very few systems (uranium, potassium, rubidium) whose radioactive decay seems to indicate ages in the billions of years. As noted in items 25 and 26 in Table I, even these methods (when based on real empirical evidence) yield young ages.

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 direct creation — already necessitated by many other scientific considerations — is therefore also indicated by chronometric data. (97, p. 251-252; also 95, p. 53-54)

Table 9: Some Representative Ages of the Earth as Proposed by Creationists

Age of:	Age (years)	Reference
Earth	10,000	Barnes(13)
Earth	10,000	Morris (92)
Earth	13,000	Camping (22)
Earth	10,000 - 20,000	Kofahi and Segraves (77)

Galaxies	nearly 6,000	Gentry (53)
Cosmos	6,000 - 10,000	Slusher (116)
Earth	7,000 - 10,000	Slusher (117)

Table 10: "Ages of the Earth" as Tabulated by Morris and Parker (97 Table I, pp. 254-259). Similar Lists Appear in Morris (93, 95). None of These Methods and Results are Scientifically Valid.

No.	Process	Indicated age of the Earth (years)	Reference
1.	Decay of the Earth's magnetic field	10,000	13
2.	Influx of radiocarbon to the Earth system	10,000	29
3.	Influx of meteoritic dust from space	Too small to calculate	92
4.	Influx of juvenile water to the oceans	340,000,000	92
5.	Influx of magma from the mantle to form the crust	500,000,000	92
6.	Growth of oldest living part of the biosphere	5,000	92
7.	Origin of human civilizations	5,000	92
8.	Efflux of He into the atmosphere	1,750 - 175,000	27
9.	Development of the total human population	4,000	94
10.	Influx of sediment to the ocean via rivers	30,000,000	99
11.	Erosion of sediment from the continents	14,000,000	99
12.	Leaching of sodium from the continents	32,000,000	132
13.	Leaching of chlorine from the continents	1,000,000	132
14.	Leaching of calcium from the continents	12,000,000	132
15.	Influx of carbonate to the ocean	100,000	132
16.	Influx of sulfate to the ocean	10,000,000	132
17.	Influx of chlorine to the ocean	164,000,000	132

18.	Influx of calcium to the ocean	1,000,000	132
19.	Influx of uranium to the ocean	1,260,000	17
20.	Efflux of oil from traps by fluid pressure	10,000 - 100,000	28
21.	Formation of radiogenic lead by neutron capture	Too small to measure	28
22.	Formation of radiogenic strontium by neutron capture	Too small to measure	28
23.	Decay of natural remanent paleomagnetism	100,000	28
24.	Decay of C in Precambrian wood	4,000	28
25.	Decay of uranium with initial “radiogenic” lead	Too small to measure	116
26.	Decay of potassium with entrapped argon	Too small to measure	116
27.	Formation of river deltas	5,000	4
28.	Submarine oil seepage into the ocean	50,000,000	133
29.	Decay of natural plutonium	80,000,000	7
30.	Decay of lines of galaxies	10,000,000	9
31.	Expanding interstellar gas	60,000,000	68
32.	Decay of short-period comets	10,000	114
33.	Decay of long-period comets	1,000,000	116
34.	Influx of small particles to the Sun	83,000	116
35.	Maximum life of meteor showers	5,000,000	116
36.	Accumulation of dust on the Moon	200,000	116
37.	Instability of the rings of Saturn	1,000,000	116
38.	Escape of methane from Titan	20,000,000	116
39.	Deceleration of the earth by tidal friction	500,000,000	14
40.	Cooling of the Earth by heat efflux	24,000,000	14
41.	Accumulation of calcareous ooze on the sea floor	5,000,000	45
42.	Influx of sodium to the ocean via rivers	260,000,000	22, 108

43.	Influx of nickel to the ocean via rivers	9,000	22, 108
44.	Influx of magnesium to the ocean via rivers	45,000,000	22, 108
45.	Influx of silicon to the ocean via rivers	8,000	22, 108
46.	Influx of potassium to the ocean via rivers	11,000,000	22, 108
47.	Influx of copper to the ocean via rivers	50,000	22, 108
48.	Influx of gold to the ocean via rivers	560,000	22, 108
49.	Influx of silver to the ocean via rivers	2,100,000	22, 108
50.	Influx of mercury to the ocean via rivers	42,000	22, 108
51.	Influx of lead to the ocean via rivers	2,000	22, 108
52.	Influx of tin to the ocean via rivers	100,000	22, 108
53.	Influx of aluminum to the ocean via rivers	100	22, 108
54.	Influx of lithium to the ocean via rivers	20,000,000	22, 108
55.	Influx of titanium to the ocean via rivers	160	22, 108
56.	Influx of chromium to the ocean via rivers	350	22, 108
57.	Influx of manganese to the ocean via rivers	1,400	22, 108
58.	Influx of iron to the ocean via rivers	140	22, 108
59.	Influx of cobalt to the ocean via rivers	18,000	22, 108
60.	Influx of zinc to the ocean via rivers	180,000	22, 108
61.	Influx of rubidium to the ocean via rivers	270,000	22, 108
62.	Influx of strontium to the ocean via rivers	19,000,000	22, 108
63.	Influx of bismuth to the ocean via rivers	45,000	22, 108
64.	Influx of thorium to the ocean via rivers	350	22, 108
65.	Influx of antimony to the ocean via rivers	350,000	22, 108
66.	Influx of tungsten to the ocean via rivers	1,000	22, 108
67.	Influx of barium to the ocean via rivers	84,000	22, 108

68.	Influx of molybdenum to the ocean via rivers	500,000	22, 108

The problem with these 68 "ages" of the Earth is that they are all either based on false initial assumptions or have too many unknown variables for a reliable solution, or both. Nearly all these methods have been aired in the scientific literature and found to be so worthless that scientists do not use them for determining the age of the Earth.

An inspection of the reference lists provided by Morris (93, 95) and Morris and Parker (97) shows that most of the calculations were done and published by Morris and his colleagues. Those calculations that are attributed to scientific journals do not actually appear there but, instead, represent unjustified interpretations by creationists of legitimate scientific data.

In addition, Morris (95) and Morris and Parker (97) draw an unwarranted parallel between their calculations and radiometric dating. Most of their "ages" rely on the assumption of constant rates for processes known to vary. Radiometric dating, in contrast, is based on a process (radioactive decay) known not to vary significantly with changes in physical or chemical conditions.

Creationists (e.g., 97) frequently claim that "evolutionists"[10] use the principle of uniformity to interpret scientific data, but these authors badly misrepresent the modern meaning of uniformitarianism. The principle of uniformity was developed in the late 18th and early 19th centuries, when geologists finally realized that the rocks and features of the Earth were formed by processes similar to those observable today operating over long periods. This was an important breakthrough in scientific thought because it meant that the Earth's history could be explained as the result of understandable, natural processes, rather than unknowable, supernatural, catastrophic evens. Creationists, however, typically state or imply that the principle of uniformity, as used by scientists, means that the rates of natural processes are always constant. Hubbert (66) reviewed the principle of uniformity and concluded that it is no longer a useful principle.

> History, human or geological, represents our hypothesis, couched in terms of past events, devised to explain our present-day observations. What are our assumptions in such a procedure? Fundamentally, they are two:
>
> (1) We assume that natural laws are invariant with time
>
> (2) We exclude hypotheses of the violation of natural laws by Divine Providence, or other forms of supernaturalism. (66, p. 31)

The principle of uniformity, if it has any meaning at all in modern science, includes no more than these two principles. Indeed, most modern scholars of the subject have concluded that uniformitarianism today is simply the application of the scientific method to nature and that the term is so confusing it should be abandoned (for example, Gould, 59, p. 111). Thus, in assuming and then condemning constant rates for geologic processes, Morris and Parker (97) and their colleagues have set up a straw man based on an obsolete historical definition of uniformity that no modern geologist would accept.

In the remainder of this chapter I examine 49 of the "ages" of the Earth advanced by creation "scientists", using Morris and Parker's (97) tabulation (Table 10) as a guide. I will show that all 49 of these ages are invalid and that most are probably best described as silly. I do not discuss the remaining ages listed in Table 10 either because they are not within my area of expertise or because I simply did not have time to investigate them. I think it is reasonable to assume, however, that the 70 percent or so I did investigate are representative and that the methods I do not discuss are likewise meaningless.

DECAY OF THE EARTH'S MAGNETIC FIELD
(Table 10, no. 1)

Other Links:

On Creation Science and the Alleged Decay of the Earth's Magnetic Field
: A debunking of the common young-earth creationist claims that a decaying magnetic field shows that the the Earth is young.

Barnes (13, 14) claims 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. (13, p. 25)

Similar statements are made by Morris (92), Slusher (117), and Kofahl and Segraves (77), who cite Barnes (13) as their source.

Barnes' (13) 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. This decrease amounts to about 6 percent between 1835 and 1965. Following an 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 for a magnetic star, and uses that time (8000 B.C.) to arrive at an upper limit for the age of the Earth.

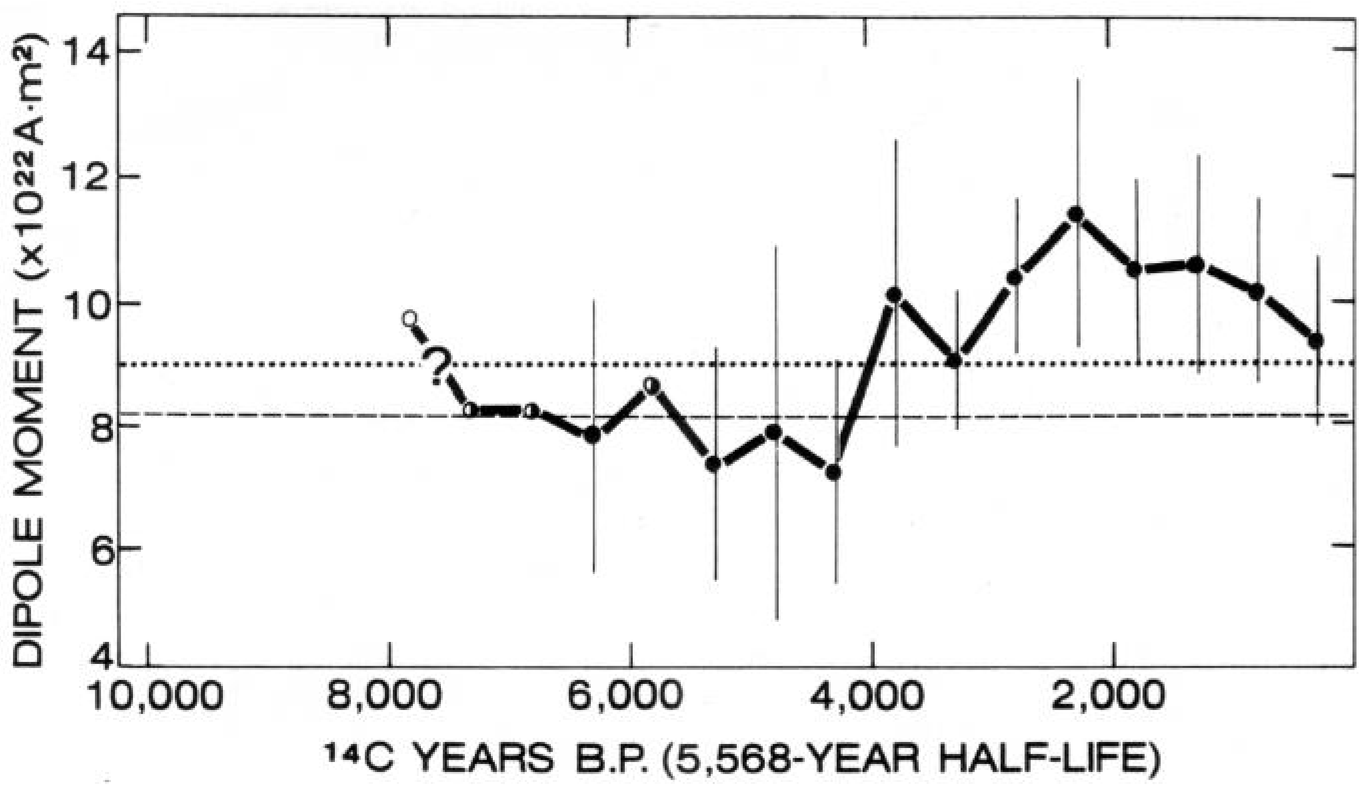
In another report (33) I show in detail how Barnes' (13) calculations and conclusions are flawed by false initial assumptions and an overly simplified view of magnetic-field behavior. Thus, it will suffice to summarize briefly the evidence against Barnes' propositions.

To a first approximation, the Earth's field is that of a dipole[11] 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 shape of the dipole field is not ideal but is highly distorted by irregularities superimposed on the dipole field. These irregularities, collectively called the nondipole 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 nondipole field is slowly and constantly changing. The Earth's magnetic field we actually observe at any spot on the Earth is the sum of dipole and nondipole fields.

As if this behavior were not complex enough, the Earth's dipole field does other remarkable things. For example, it occasionally reverses polarity, so that the north pole becomes the south pole and vice versa (30). Paleomagnetic measurements on lava flows indicate that these polarity reversals have occurred at irregular but frequent intervals. Barnes (13) denies that the Earth's field has reversed, but he fails to cite the relevant literature on the subject and does not refute the numerous observations that prove field reversal.

The field also changes intensity or strength, though not in the way Barnes (13) claims. A careful analysis of the Earth's field by McDonald and Gunst (85) showed that the decrease in the dipole moment over the past 50 years has been balanced by a corresponding increase in the nondipole component of the field, so that the total energy of the field external to the Earth's core has been approximately constant. Over the past 120 years, however, it appears that the nondipole-field increase has not been quite sufficient to balance the dipole-field decrease, and so the total field appears to have been decreasing at an average annual rate of about 0.01 percent (129), much less than the value used by Barnes (13). Is there any reason to conclude that this short-term decrease is permanent, as Barnes claims? 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 indicate that the Earth's dipole moment over the past 8000 years or so has not been continuously decaying but, instead, has been fluctuating (Figure 9). How much of this fluctuation is balanced by the nondipole field and how much is a fluctuation in the total magnetic-field energy is not known, but the field certainly does not behave as Barnes (13) claims. Barnes makes the fundamental error of equating the strength of the dipole field with the strength of the total field and, in doing so, ignores the nondipole field, a major component. He also errs in equating the strength of the dipole field with the total-field energy, most of which is probably locked up in a toroidal component internal to the liquid core and, thus, unobservable from the surface of the Earth.

Figure 9: Geomagnetic dipole moment estimated from 500-year global averages of measurements on lava flows and archeological materials, such as bricks and pottery. Vertical lines are standard deviations. Dots are averages from three or more regions of the Earth, half-filled circles two regions, and circles a single region. The dotted line is the average of all the data; the dashed line is the value for the 1965 field. After Champion (25).



The magnetic record in rocks[12] clearly indicates that the Earth's magnetic field during Precambrian times was within about 50 percent or so of its present strength (88). These observations are consistent with theoretical considerations, which show that the Earth's field is probably generated by a self-exciting fluid dynamo in the Earth's liquid-metal core and that the necessary energy comes from either radioactive heat within the Earth or gravitational energy, or both. Some time in the future, the magnetic field of the Earth may begin to decrease permanently as the Earth's available energy is used up, but it will be billions of years before that happens.

The Earth cannot be dated by its magnetic field, and Barnes' (13) calculations are meaningless, as is his maximum age for the Earth.

INFLUX OF METEORITIC DUST
(Table 10, nos. 3, 36)

Other Links:

Meteorite Dust and the Age of the Earth
A detailed look at creationist fallacy.

Moon dust and the age of the solar system

The young-earth creationist organization, Answers in Genesis, says that meteorite dust arguments are flawed and should no longer used by creationists.

Morris and Parker (97) list two age calculations based on the influx of meteoritic dust to the Earth ("Too small to calculate") and the Moon (200,000 years), referenced to Morris (92) and Slusher (116), respectively. Morris (92) argues that the age of the Earth cannot be great because if it were, there would be a thick layer of meteoritic dust on both the Earth and the Moon. Table 11 lists the data he uses. Morris' values for the density of the dust and the area of the Earth are reasonable, and his slight exaggeration of the age of the Earth is unimportant to this discussion. The real problem is with his value for the influx of meteoritic dust from space, which Morris takes from Petterson (105).

Petterson (105) collected particulate matter from the top of Mauna Loa on the Island of Hawaii, using an air pump designed to sample smog. He analyzed the dust content in a known volume of air for the element nickel. Using a value of 2.5 percent for the nickel content of meteoritic material and assuming that all nickel in the atmospheric dust comes from space, he calculated that about 15 million tons of meteoritic dust falls on the Earth each year. Petterson (105) concluded that his calculation was an upper limit and, after evaluating all the available data, stated that a value of 5 million tons per year was more reasonable. Note that Morris (92) didn't get Petterson's upper limit of 15 million tons per year correct and that he completely ignored Petterson's preferred value.

Although there is probably nothing fundamentally wrong with Petterson's (105) measurements, his assumptions that nickel is a rare element in the Earth's crust and in atmospheric dust, and that all the nickel can be attributed to dust from space, are incorrect. More significant is the fact that Petterson's (105) measurements were made in 1957, the same year that the first satellite was launched. Since the late 1960s, much better and more direct measurements of the meteoritic influx to the Earth have been available from satellite penetration data. In a comprehensive review article, Dohnanyi (39) showed that the mass of meteoritic material impinging on the Earth is only about 22,000 tons per year, a value that would result in a layer only 8.1 centimeters thick in 4.55 billion years (Table 11). Other recent estimates of the mass of interplanetary matter reaching the Earth from space, based on satellite-borne detectors, range from about 11,000 to 18,000 tons per year (67); estimates based on the cosmic-dust content of deep-sea sediment are comparable (e.g., 11, 103). Thus, Morris (92) is off by a factor of more than 600. His conclusion about the thickness of dust on the Moon is likewise in error; he apparently neglects gravitational effects, which reduce the influx per unit area to the Moon by a factor of about 2.

Table 11: Comparison of Creationist and Scientific Versions of Meteoritic Dust on the Earth and the Moon. Following Morris (92), These Calculations are Based on the Highly Questionable Assumptions that the Influx of Dust has been Constant Throughout Geologic History and that No Erosion has Occurred

	Creationist version (92)
Influx of dust to the Earth	14×10^6 tons/yr
Density of the dust	140 lb/ft^3
Area of the Earth	5.5×10^{15} ft^2
Age of the Earth	5×10^9 yr
RESULTS: 1) Layer on the Earth 182 ft (5048 cm) thick 2) Layer on the Moon at least as thick	
	Scientific version
Influx of dust to the Earth	4×10^{-9} g/cm^2·yr (20,084 tons/yr)
Influx of dust to the Moon	2×10^{-9} g/cm^2·yr (2,989 tons/yr)
Density of the dust	2.24 g/cm^3 (140 lbs/ft^3)
Area of the Earth	5.10×10^{18} cm^2 (5.49×10^{15} ft^2)
Area of the Moon[‡]	1.52×10^{18} cm^2 (1.63×10^{15} ft^2)
Age of the Earth and the Moon	4.55×10^9 yr
RESULTS: 1) Layer on the Earth 8.1 cm thick 2) Layer on the Moon 4.1 cm thick	

Slusher (116) likewise fails to avail himself of current knowledge on the subject and, instead, uses obsolete dust-influx estimates ranging from 3.6 million to 256 million tons per year. In addition, he advances the erroneous argument that the impact of meteoritic material and radiation from space should have created, by pulverization, a layer of regolith ("soil") many miles thick if the Moon is 4.5 billion years old.

> If a layer, say 0.0004 inch thick of pulverized matter, is formed per year, then, in 10,000 years a layer about four inches in depth would be produced; in 100,000 years a layer of 40 inches; in 1,000,000 years a layer of 3.3 feet; in 4,500,000,000 years a layer about 28 miles in depth would be formed. (116, p. 42)

He apparently fails to realize, however, that once a layer of pulverized material is formed, repeated impacts primarily will stir the existing layer rather than increase its thickness. As Dutch (41) has pointed out, Slusher's (116) argument is equivalent to arguing that if a farmer plows his field to a depth of 20 centimeters each spring, in 100 years he (and his successors) will have plowed to a total depth of 20 meters.

Considering that good satellite data on meteoritic influx were available before Morris (92) and Slusher (116) published their papers, they obviously have been highly selective in their choice of obsolete data. A more fundamental point, however, is that such calculations are based on faulty premises, including the erroneous assumptions that the meteoritic influx has remained constant for 4.5 billion years and that erosion is negligible, and thus are of no value in determining the age of the Earth or the Moon.

Finally, I have been unable to find the 200,000-year "age of the Earth" based on the accumulation of dust on the Moon (No. 36, Table 10) in Slusher's (116) paper, nor can I find any data from which this result could have been obtained. Apparently, Morris and Parker (97) have credited Slusher (116) with a calculation that he did not do.

INFLUX OF MAGMA TO THE CRUST
(Table 10, no. 5)

Morris and Parker (97) list an age of 500 million years based on the "influx of magma from mantle to form crust." This calculation, which appears in Morris (92), is based on the volume (0.2 km^3/yr) of lava erupted by Paricutin Volcano in Mexico during the 1940s. Morris (92) notes that intrusive rocks are much more common than lava flows:

> … so that it seems reasonable to assume that at least 10 cubic kilometers of new igneous rocks are formed each year by flows from the earth's mantle.
>
> The total volume of the earth's crust is about 5×10^9 cubic kilometers. Thus, the entire crust could have been formed by volcanic activity at present rates in only 500 million years, which would only take us back into the Cambrian period. On the other hand, all geologists would surely agree that practically all the earth's crust had been formed billions of years before that time. The uniformitarian model once again leads to a serious problem and contradiction. (92,p. 157)

But the "uniformitarian model" of which Morris (92) is so critical is a product of Morris (92), not science. He has pulled the value of 10 km^3/yr from thin air, assumed that this fictitious rate has been constant over time, and neglected erosion, sedimentation, crustal recycling, and the fact that the injection of magma into the crust is a highly nonuniform process about which little is known. Morris' (92) calculation is worthless.

EFFLUX OF ^4He INTO THE ATMOSPHERE
(Table 10, no. 8)

This age is referenced to a report by Cook (27), but the calculation was done by Morris (92), using data from Cook's paper:

> Consequently the maximum age of the atmosphere, assuming no original helium in the atmosphere, would be

$$\left(\frac{3.5 \times 10^{15}}{10^{20}}\right) \times \left(5 \times 10^{9}\right) = 1.75 \times 10^{5} \text{years}$$

> As a matter of fact, Henry Faul (Faul, 1954) has cited evidence that the rate of efflux of helium into the atmosphere … is about 100 times greater than the value used by Cook. This in turn would reduce the age of the atmosphere down to several thousand years! (92, p. 151)

The values in this calculation are the content of ^4He in the present atmosphere (3.5×10^{15} g) and the estimated total efflux (10^{20} g) from the Earth's crust and mantle throughout geologic time (5×10^9 years). Morris' (92) calculation is based on the assumption that all the helium released into the atmosphere would be retained, an assumption known to be false.

The helium balance in the atmosphere has been a subject of much study (76). Calculations show that at the present rates of production[13], the entire atmospheric content of ^4He and ^3He could be supplied in about 2.3 million and 0.7 million years, respectively. Various mechanisms are known, however, by which helium escapes from the atmosphere into outer space.

At normal temperatures, the velocity of the average helium atom is less than the velocity required for escape from the Earth's gravitational field. The elevated temperature in the exosphere, however, increases the kinetic energy of the helium atoms, so that some do escape. Calculations show that this mechanism could account for the escape of about half the ^3He produced. Because ^{4} He is about a third heavier than ^3He, however, thermal escape is probably insufficient by a factor of about 40 to account for the loss of ^4He. The apparent inadequacy of thermal escape is the basis for Cook's (27) report and Morris' (92) calculation, but these authors have overlooked other mechanisms.

The most probable mechanism for helium loss is photoionization of helium by the polar wind and its escape along open lines of the Earth's magnetic field. Banks and Holzer (12) have shown that the polar wind can account for an escape of 2 to 4×10^6 ions/cm^2·sec of ^4He, which is nearly identical to the estimated production flux of $(2.5 \pm 1.5) \times 10^6$ atoms/cm^2·sec. Calculations for ^3He lead to similar results, i.e., a rate virtually identical to the production flux. Another possible escape mechanism is direct interaction of the solar wind with the upper atmosphere during the short periods of lower magnetic-field intensity while the field is reversing. Sheldon and Kern (112) estimated that 20 geomagnetic-field reversals over the past 3.5 million years would have assured a balance between helium production and loss.

Calculations involving the helium balance in the atmosphere are complex because they are sensitive to solar activity, geomagnetic-field fluctuations, the rate of helium production from the Earth, and other factors. Although the helium-balance problem is not yet completely solved, it is clear that helium can and does escape from the atmosphere in amounts sufficient to balance production. The main problem is that the exact roles of the several known mechanisms are unknown. The helium balance of the atmosphere certainly is not a basis for calculating any reasonable estimate of the Earth's age. Any attempt to do so (92) requires an unjustified oversimplification of a complex problem.

ACCUMULATION OF SEDIMENT AND EROSION OF THE CONTINENTS
(Table 10, nos. 10 and 11)

These "ages" are based on some calculations by the creation "scientist" Nevins (99), who used the following basic data:

1) Present influx of sediment to the ocean = 27.5×10^9 tons/yr
2) Present mass of sediment in the ocean = 820×10^{15} tons
3) Present mass of the continents above sea level = 383×10^{15} tons

Dividing (2) by (1), Nevins (99) calculates that all the sediment now in the world's oceans could have accumulated in 30 million years; dividing (3) by (1), he finds that the present continents could be leveled in 14 million years. From these results, Nevins (99) concludes:

> After careful analysis of the erosion of continents and associated sedimentation in the world ocean, we must ask two urgent questions. Where is all the sediment if, as the evolutionist assumes, the ocean is over 1 billion years old? Who has the better model for the ocean — the evolutionist or the creationist? We feel confident that the true answers concerning the origin of the ocean are presented in Scripture. "The sea is His and He made it" (Psalm 95:5). (99, p. iv)

Both the basic assumptions and logic of Nevins' (99) arguments are wrong. First, he has confused the length of time over which the ocean has existed on the Earth with the ages of the present ocean floors. The existence of abundant Precambrian marine sediment, some more than 3.5 billion years old, clearly demonstrates that the early Earth had an ocean. Some of this earliest sediment contains structures that indicate the presence of algae, and there are undisputed microfossils in sedimentary rocks more than 2 billion years old (26). The Earth, however, is a dynamic body, and the ocean basins are among its youngest features. The floors of the world's ocean range in age from recent at the crests of midoceanic ridges, where new oceanic crust is forming, to as old as Jurassic (Figure 1) in the parts farthest from the ridges. The sediment in the ocean is practically nonexistent at the ridges and thickens, away from the ridges as the age of the sea floor increases. At the trenches, the sea floors, sediment and all, are being forced down into the mantle where they are consumed to be recycled. Thus, the ocean floors are neither so old nor so passive as Nevins' (99) calculations presume, and the age of 1 billion years attributed by him to "evolutionists" is of his own invention.

Second, Nevins (99) has assumed constant rates for erosion and sedimentation, processes whose rates have, in fact, varied constantly throughout geologic time.

Finally, Nevins (99) has neglected the fact that the continents are also dynamic and have grown appreciably over time, both by accretion of material at the margins and by addition of material from the mantle below. Uplift, primarily by buoyant and compressional forces, is also a significant factor that tends to offset the leveling effect of erosion.

Thus, the deposition of sediment in the ocean basins and the erosion of continents are parts of a larger, dynamic, and cyclic process that is continually changing the face of the Earth. The mass of sediment in the ocean is not unexpectedly low, nor is the mass of the continents above sea level unexpectedly high. Nevins' (99) calculations provide no useful information about the age of either the Earth or its ocean.

INFLUX OF URANIUM TO THE OCEAN
(Table 10, no. 19)

Morris and Parker (97) present two calculations based on data from a report by Bloch (17), a geologist with the Oklahoma Geological Survey. Using Bloch's (17) values for the amount of dissolved uranium in the ocean (3.64×10^{15} g), and the present influx of uranium to the ocean (1.92×10^{10} g/yr), Morris and Parker (97) state:

> Dividing the first number by the second gives about 189,000 years as the maximum age of the ocean, even with the, very unlikely assumptions that the ocean contained no uranium when it was formed and the river influx was no greater in the past than at present (actually, all the world's rivers give abundant evidence of carrying much greater flows in the earlier years of their history). The true age would most likely be much smaller than this. (97, p. 249)

Morris and Parker (97) also comment on the possibility that uranium was being removed from the ocean; again, citing Bloch:

> However, the old-earth proponent would undoubtedly counter by insisting that much of the dissolved uranium would probably be precipitated out in estuarine or oceanic sediments. Bloch, in fact, has carefully determined the effect of all such possibilities.
>
> A detailed mass-balance calculation for uranium has shown that only about 10% of the present-day river input of dissolved uranium can be removed by known sinks.
>
> That is not all, however.
>
> Low and high-temperature alteration of basalts, organic-rich sediments and co-existing phosphorites on continental margins, metalliferous sediments, carbonate sediments, and sediments in anoxic basins deeper than 200 meters remove about three-fourths of the present-day riverine supply to the ocean.
>
> Since these would seem to exhaust the possibilities, at least 15% of the annual riverine influx of uranium is still available to build up the ocean's uranium content. Making this allowance, the maximum possible age of the ocean, based on this type of uranium dating, becomes 189,000 + 0.15, or 1,260,000 years. (97, pp. 249-250)

Morris and Parker's (97) first calculation is made worthless by their assumptions of constant rates of influx and the absence of uranium removal. The second calculation suffers from a more serious flaw: The second quotation from Bloch (17) is incomplete. The next two sentences of Bloch's (17) statement read as follows:

The remainder can most likely be accounted for by the combined uncertainties in the estimates of U sources and sinks. It appears that the steady state of the world ocean with respect to U can still be maintained in spite of the fact that anthropogenic contributions of this element may be significant. (17, p. 376)

In other words, the uncertainties in the estimates of the rates of influx and removal do not permit Morris and Parker's (97) conclusion that the uranium in the ocean is not in balance. So far as it known, the amount of uranium in the ocean is in a steady state.

Finally, I should point out that Morris and Parker's (97) arithmetic is faulty. They apparently have added the 10 percent from the first quotation (which actually is the portion attributable to carbonate sediment and anoxic basins only) to the 75 percent in the second quote to obtain their 15 percent "imbalance." In Bloch's (17) report however, the 75 percent value includes all sinks, and so the "remainder" that falls within the uncertainties of the data is 25 percent, not 15 percent.

INFLUX OF OTHER ELEMENTS TO THE OCEAN
(Table 10, nos. 15-18 and 42-68)

In addition to uranium, discussed above, Morris and Parker (97) list 31 other "ages" of the Earth based on the influx of various elements and compounds to the ocean via rivers. These ages range from 100 years (aluminum) to 260 million years (sodium) and are cited as evidence for a young Earth:

Similar calculations can be made for all the other dissolved chemicals in the ocean. All will yield relatively small ages (at least in comparison to usual evolutionary estimates of the age of the ocean) but all will, of course, yield different ages. Again, however, even allowing for all realistically possible "sinks," sedimentation, recycling, etc., none will yield an age anywhere close to the billion-year ages required for evolution.

Attempts to "date" the Earth using the dissolved chemicals in the ocean were common in the late 19th and 20th centuries. Probably the best known example is the calculation by Joly (71) that the Earth's age is 89 million years, based on the amount of sodium in the ocean. It has been known for many decades, however, that such calculations are wrong because the ocean is in approximate chemical balance, as clearly recognized by Cook:

The validity of the application of total salt in the ocean in the determination of age turned out to have a very simple answer in the fact shown by Goldschmidt (1954) that it is in steady state and therefore useless as a means of determining the age of the oceans. (28, p. 73)

The primary documentation referenced for ages 42 through 68 (Table 10) is the book edited by Riley and Skirrow (108). Neither Morris (92, 95) nor Morris and Parker (97) discuss the calculations that led to these 27 ages, perhaps because there are no such calculations. The values given by these authors are copied directly from a chapter by Goldberg (55) that appears in Riley and Skirrow (108). Goldberg's (55) Table I is a list of the abundances and residence times of the elements in sea water; it is these residence times that Morris (92, 95) and Morris and Parker (97) give as indicated ages of the Earth. The residence time of an element, however is the average time that any small amount of an element remains in seawater before it is removed, not, as stated by Morris (92), the time "to accumulate in ocean from river inflow," and has nothing to do with the ages of either the Earth or the ocean. Morris (92, 93, 95) and Morris and Parker (97) have totally misrepresented the data listed in Goldberg's (55) table. Morris and Parker (97) also reference a paper by the creationist Camping (22), who also confuses residence times with "times to accumulate" and fails to realize that the chemicals in the ocean are basically in a state of dynamic balance.

The documentation cited by Morris and Parker (97) for carbonate, sulfate, chlorine, and calcium (Nos. 15 -18, Table 10) is a book by the creationist author Whitney (132), whose calculations also are meaningless because they suffer from the same inadequacies discussed above.

As I pointed out above, the influx of chemicals into the ocean cannot be used to calculate the age of the Earth because the ocean is in approximate, if not exact, chemical equilibrium. For example, virtually the entire world's supply of chlorine (Table 10, no. 17) is in the ocean, and nearly all the chlorine carried by rivers is of cyclic origin (55). Chlorine simply evaporates from the ocean, and falls in rainwater either directly back into the ocean or runs into rivers, where it is returned to the sea. Aluminum enters the sea primarily as particulate matter from the weathering and erosion of rocks. It quickly either settles out as sediment or reacts with other elements to form new minerals, and thus has a residence time in ocean water of only about 100 years.

The influx of chemicals to the ocean is an invalid and worthless method of determining the age of the Earth. Morris (92, 95) and Morris and Parker (97) have misrepresented fundamental geochemical data and ignored virtually everything that is known about the geochemistry of seawater.

FORMATION OF RADIOGENIC Pb AND Sr BY NEUTRON CAPTURE
(Table 10, nos. 21 and 22)

These "ages" are referenced to the book by Cook (28). I have discussed the flaws in Cook's (28) reasoning concerning the effects of neutron reactions on lead isotope ratios in a previous section above. I could not find any mention in his book of a similar effect on strontium isotopes, and so how and where Morris and Parker (97) obtained this "too small to measure" age is, at present, a mystery.

DECAY OF U WITH INITIAL Pb AND DECAY OF K WITH TRAPPED Ar
(Table 10, nos. 25 and 26)

The ages of the Earth resulting from these two "methods" are given as "too small to measure," and the calculation is referenced to Slusher (117). I have read both the 1973 and 1981 editions of Slusher's monograph several times and cannot find these age-of-the-Earth calculations nor any data from which such a calculation could conceivably be made. Apparently, Morris and Parker (97) have credited their colleague with calculations that he did not do.

FORMATION OF RIVER DELTAS
(Table 10, no. 27)

The reference for this "age of the Earth" of 5,000 years is a paper by Allen (4) that was originally published in the Bulletin of Deluge Geology and Related Sciences (v. 2, no. 2, p. 37-62) in September of 1942, and reprinted in 1972 in the Creation Research Society Quarterly. Benjamin Allen was a lawyer who for years was the head of the Deluge Society of Los Angeles (4).

Allen (4) reviews the mid-19th century controversy between Charles Lyell, the noted British geologist and close friend of Charles Darwin, and General Andrews Humphreys of the U. S. Army Corps of Engineers concerning the age of the Mississippi River delta. Based on a total sediment thickness of 528 ft, Lyell calculated that the delta and, therefore, the Mississippi River, are 61,000 years old. Adopting the arguments of Humphreys, Allen (4) asserts that only the uppermost 40 ft are delta sediment, and that the underlying sediment is of marine origin. On this basis, he concludes that the Mississippi River and its delta, as well as the other major rivers of the world, originated at the close of the flood 4500 to 5000 years ago. Central to Allen's (4) thesis is his rejection of the role of subsidence in the accumulation of delta sediment.

There is no disagreement that the present delta of the Mississippi River is relatively young. Recent studies (for example, 58) indicate that deposition began about 18,000 years ago during the last major glaciation when sea level was more than 400 ft lower than at present. Deposition has been rapid, and the sediment reaches a known thickness of 1000 ft. This thickness has been accommodated partly by the rise in sea level following the ice ages and partly by subsidence of the older formations on which the delta was deposited.

Allen's (4) article is more than four decades out of date, and he draws much of his data and arguments from papers published in the 19th century. Since Allen's article was first printed in 1942, there have been an enormous number of new data published on the geological history of the Mississippi delta, many of them collected by drilling, and seismic surveys using methods unavailable in the first half of the 20th century. Thus, Allen's information about the composition, thickness, and age of the delta sediment is incorrect. Allen also ignores the fact that the present delta is but the latest depositational phase in a continuing episode of deltaic sedimentation that began in the Mississippian Period, i.e., more than 330 million years ago (107). Finally, there is absolutely no evidence that either the Mississippi River delta or the deltas of any of the world's major rivers originated simultaneously during a worldwide catastrophic flood, as Allen (4) proposes.

Even more serious for Morris and Parker's (97) "age of the Earth" is the simple and obvious fact that the age of the Mississippi River delta does not equal the age of the Earth. Even if Allen's (4) age of 4500 to 5000 years for the delta were correct, it would still represent only the age of the delta and would not support Morris and Parker's (97) contention that the Earth is very young. Thus, not only is their "age" of 5000 years for the Earth meaningless, but also their logic defies reason.

SUBMARINE OIL SEEPAGE
(Table 10, no. 28)

This age of the Earth is referenced by Morris and Parker (97) to a report by Wilson and others (133), who estimated the present rate of petroleum seepage into the marine environment at about 0.6 million metric tons per year. The value of 50 million years listed by Morris and Parker (97) as an indicated age of the Earth apparently comes from the following statement by Wilson and others (133):

> … the amount of oil available for seepage reflected by these reserve estimates is about 2×10^{14} barrels or nearly 3×10^{13} metric tons. This volume of oil alone could have sustained a seepage rate of 0.6×10^{6} years… (133, p. 864)

Morris and Parker (97), however, have chosen to ignore the remainder of the discussion by Wilson and his colleagues:

> However, the total oil available for seepage and the time span would be substantially greater since the reserve estimates … include less than half of the offshore area that is considered to be seepage-prone. Moreover, the above reserve figures do not include oil from tar sands and oil shales, which are also potential seepage sources. … (The) inclusion of all potential sources would sustain the seepage rate of 0.6×10^{6} metric tons per year for a period of time equivalent to the Tertiary and much of the Mesozoic … when a large percentage of the off-shore oil was being generated. (133, p. 864)

Wilson and others (133) also note that there is no basis for presuming that the seepage rate has been constant and that their calculation was done only to determine whether or not their estimate of the seepage rate is reasonable. Recall that the present ocean basins of the world are relatively young, ranging in age from Holocene to Jurassic. The shelves of the continents, where most off-shore oil is found, also are primarily Mesozoic and younger. Thus, the calculations and conclusions of Wilson and others (133) are consistent with what is known about the age of the rocks in which offshore oil is generated and found.

Morris and Parker (97) have blatantly misrepresented legitimate scientific data and conclusions. The present rate of offshore oil seepage cannot be used to calculate an age for the Earth.

DECAY OF NATURAL PLUTONIUM
(Table 10, no. 29)

The reference for this age of the Earth is a short news item in Chemical and Engineering News, which, in its entirety, reads as follows:

> Plutonium occurs in nature. Dr. Darlean Hoffman and Francine Lawrence at the Los Alamos Scientific Laboratory have chemically isolated about 8×10^{-15} grams of plutonium-224 [sic] from 85 kg. of bastnasite ore from the Mountain Pass, California, mine of Molybdenum Corporation of America. Jack McWherter and Frank Rourke at the Knolls Atomic Power Laboratory, Schenectady, New York, identified the isotope by mass spectrometry. Detection of this relatively short-lived isotope (80 million years) may indicate that synthesis of heavy elements was still occurring at the time of formation of the Solar System. (7, p. 29)

The discovery of natural plutonium-244 was significant partly because it was the heaviest isotope ever found in nature but mostly because it gave scientists a valuable clue about the time of synthesis of the heavy elements. The reasoning is as follows. If the radioactive isotope plutonium-244 was synthesized at the time of formation of the Solar System, then, with a half-life of 80 million years, the 8×10^{-15} g represents the undecayed remainder of 1057 g^{14}, or slightly more than 2 lb — a conceivable amount. On the other hand, if the plutonium-244 was synthesized at the time of formation of the Galaxy, about 12 ± 2 billion years ago, then the original amount would have to be 1.14×10^{31} g or 1.26×10^{25} tons! Thus, the discovery of plutonium-244 in nature suggests that it may have been synthesized as the Solar System formed rather than much earlier.

What Morris and Parker (97) have listed as an 80-million-year indicated age of the Earth is simply the half-life of plutonium-244. Clearly, they do not understand either the content or the significance of the discovery reported in the brief news article they cite as their source of documentation.

COOLING OF THE EARTH
(Table 10, no. 40)

This age is attributed to Barnes (14). Barnes (14) 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 (127). 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 is probably no more than 100 million years old and almost certainly no more than 500 million years old (126). 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. The value of 24 million years, preferred by Barnes (14) and listed by Morris and Parker (97) as the age of the Earth, is attributed by Barnes to Kelvin but was, in fact, first published by King (73). Lord Kelvin (82), however, agreed with King's value and adopted it as a likely upper limit for the age of the Earth.

Kelvin and several noted geologists, including Chamberlain (24), 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 dispute was resolved in 1903, when Rutherford and Soddy (109) first determined the amount of heat generated by radioactive decay. Rutherford and Soddy readily appreciated the significance of their discovery for cosmologic 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 subatomic change are going on. (109, p. 591)

Subsequent measurements of the amount of radioactive uranium, thorium, and potassium in the Earth and in meteorites have shown that all the heat flowing from the interior of the Earth outward can easily be accounted for by radioactive decay, although gravitational energy and latent heat of crystallization probably are also important. Barnes (14), 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. (14, iii)

The first statement is simply untrue. There is a large volume of 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 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 (21), 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.

The pre-20th-century history of the various attempts by scientists and philosophers to estimate the age of the Earth is a fascinating subject that the reader may wish to explore in more detail (1, 48). 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 (21). Kelvin's calculations are interesting from an historical point of view, but for nearly all of the 20th century they have been known to be wrong.

In a recent creationist monograph, Slusher and Gamwell (118) consider the contribution of radioactive heat to the problem of a cooling Earth and conclude that even with radioactivity as a source of heat, the calculations lead to the conclusion that the Earth is young:

> The cooling times appear quite small (thousands of years) if the initial temperature of the earth was on the order of that for a habitable planet for any of the models. Even for initial temperatures as high as that for an initially molten earth, the cooling times are vastly less than evolutionist estimates. It would seem that the earth is vastly younger than the old earth demanded by the evolutionists. Thus, the evolutionary hypothesis would seem to be a false hypothesis for explaining things. (118, p. 75)

Their treatment of this important and complex problem, however, is inexcusably naive. They have neglected important sources of heat within the Earth, selected inappropriate depth distributions of radioactive elements, and ignored completely the loss of heat by convection in the mantle. Before discussing the flaws in their conclusions further, I here explain briefly some of the factors that scientists must consider when analyzing the Earth's thermal history, and review some current thinking on the subject.

The solution to the problem of the Earth's thermal history consists of an evaluation of the relative importance of both the various sources of heat in the Earth and the several ways in which this heat is transferred from depth to the surface. The problem is complicated by several factors: (1) the early events in the formation of the Earth, many of which would generate large amounts of heat, are poorly understood; (2) the heat generated by radioactivity decreases exponentially over time; (3) the distribution of radioactive elements within the Earth is poorly known; (4) the temperature gradient in the Earth can be measured for only the outer few kilometers; (5) many of the relevant physical properties of the mantle, such as conductivity, specific heat, and viscosity, must be estimated; and (6) the pattern of mantle convection is poorly known.

There are several important sources of heat in the Earth. One is primordial heat, i.e., heat left over from the formation of the Earth. Although the Earth probably accreted cold, radioactivity, gravitational energy from compaction, and segregation of the iron-nickel core probably generated enough heat to raise the temperature of the Earth to near the melting point within 100 to 200 million years of its formation (83, 122). In addition, the heat from impacts of large meteorites during the period when the Earth was still sweeping up large amounts of material from its orbital path generated large amounts of heat and may have resulted in the melting of the outer 100 km or so. Much of this primordial heat has not yet escaped from the Earth.

A second source of heat is radioactivity. This heat is generated by the radioactive decay of uranium, thorium, and potassium contained in the rocks of the Earth. Although the exact distribution of these radioactive elements within the Earth is not well known, there is no problem in constructing reasonable Earth models that attribute most or even all of the heat now flowing outward from the Earth to radioactive decay. For example, all the heat required could be generated by the uranium, thorium, and potassium contained in a granitic crust only 22 km thick (120). Likewise, if we assume that the Earth has a bulk composition similar to that of the primitive meteorites called carbonaceous chondrites, then the heat produced by radioactivity would about equal the present average heat flux from the mantle (119). These two examples, of course, are oversimplifications of a problem of vastly greater complexity, but they do illustrate that radioactivity is probably the single most important mechanism of heat generation in the Earth today. Because radioactive elements decay exponentially over time, radioactive decay would have generated even more heat in the past. For example, 4.5 billion years ago, the rate of heat generation from the decay of uranium, thorium, and potassium in the Earth would have been nearly 6 times the present rate (120).

In addition to primordial heat and heat from radioactivity, contraction of the Earth due to cooling and gravitational-energy release as the core grows may also be important contributors to the Earth's thermal budget.

Of equal importance as heat sources are the mechanisms by which the Earth loses heat. One is conduction, which involves the transfer of kinetic energy at the atomic and molecular level; this is the same means by which heat is transferred through the bottom of a cooking pan from the burner to the food. The conductivity of rocks, however, is rather poor, and conduction is not particularly efficient. For example, heat generated 4.5 billion years ago at a depth of a few hundred kilometers would just now be reaching the surface if conduction were the only mechanism of heat transfer within the Earth.

The most important mechanism of heat loss from the Earth is convection, which involves the transfer of heat by motion of the hot material itself. Convection is highly efficient and, to a large degree, self-regulating. When a liquid is heated in a pan, for example, the more heat is supplied, the more vigorously the liquid convects, and the faster heat is lost. Calculations show that the rocks of the mantle can be expected to show similar behavior; the more heat is supplied, the less viscous the mantle becomes, the faster it convects, and the more heat is transferred to the surface.

There is little doubt that the Earth's mantle is convecting. The evidence from continental drift, sea-floor spreading, and the bathymetry of the sea floor is conclusive. Calculations also show that mantle convection is both physically possible and probable. Although at first it may seem impossible for solid rocks to flow, both theory and laboratory experiments show that they can and do, although the mechanism differs somewhat from that involved in the flow of liquid. Estimates of the present rate of mantle convection indicate that the motion is on the order of a millimeter or so per year.

Studies of the thermal budget of the Earth consist of balancing the various heat sources against heat loss through convection and conduction, taking into consideration what is known about the history and physical properties of the Earth. Current studies indicate that of the total geothermal heat flux of 38×10^{12} W, about 63 percent or 24×10^{12} W is lost from the mantle. Only 24 percent (9×10^{12} W) is lost from the continental lithosphere, and perhaps 5×10^{12} W may be lost from the core by plumes of hot material rising from near the core-mantle boundary (122).

The heat flow per unit area from the continents is about the same as from the oceans, although both local and regional variations occur. Because the continents cover only about a quarter of the Earth's surface, about three-fourths of the total heat flow is through the ocean basins. Virtually all the heat lost from the ocean basins comes from the mantle and is brought close to the surface by convection. About 30 percent of the total global heat loss is at the midoceanic rises, where new crust is forming by the injection and eruption of magma (83, 113). Although conduction plays a role in transferring some heat through the oceanic crust, convection is the dominant mechanism bringing heat from depth. In contrast, heat loss from the continents is primarily by conduction. Of this heat, about two-thirds is generated by radioactivity within the continents themselves (121); the remainder is brought to the base of the continental lithosphere from the mantle by convection, where it is then conducted to the surface. Thus, both convection and conduction play roles in the Earth's thermal budget; however, on a global scale, most of the heat lost from the Earth is through the ocean basins, primarily by convection in the mantle.

Although radioactivity is probably the dominant source of the heat flowing from the Earth's surface, some of the heat may be primordial. Recent studies (for example, 113, 119, 122) indicate that the Earth may be cooling at a rate of 5 to 6°C per 100 million years and that primordial heat may constitute 30 to 40 percent of the heat now being lost from the Earth.

What, then, of the conclusion of Slusher and Gamwell (118) that consideration of the Earth's heat budget indicates that the Earth is very young? They have reached this conclusion by ignoring most of what is known about the chemistry, physics, and history of the Earth. First, they begin with the erroneous assumption that the only heat-loss mechanism for the Earth is conduction; they completely ignore convection. This assumption would be excusable only had their paper been written before the mid-1960s, before there was sound evidence that the Earth's mantle was convecting.

Second, Slusher and Gamwell (118) seemingly are unaware that the Earth's surface includes both continents and ocean basins, each of which have different compositions, distinct physical characteristics, and participate in global plate tectonics in quite different ways. They take no account of the differences in either heat generation or loss between these vastly different regimes of the Earth.

Third, they use inappropriate depth distributions for the radioactive elements. Only by adopting the unrealistic assumption that most radioactive isotopes are concentrated in the outer 10 km or so of the crust do their analyses yield cooling times of "thousands of years" rather than millions of years. Although it is true that uranium, thorium, and potassium tend to be enriched in the Earth's crust, there is every reason to think that the mantle also contains these elements; their concentrations may be small, but the mass of the mantle is so great that significant heat production results.

Finally, thermal analysis of the Earth cannot yield an estimate of its age. The age of the Earth, determined independently by radiometric dating, is one of the boundary conditions that must be satisfied in such an analysis; it is not a result. There are simply far too many things about the history and interior of the Earth that are poorly known and must be estimated. For example, even before convection was known to be an important factor in heat loss from the Earth, scientists were able to devise reasonable thermal models for the Earth that attributed all the heat generated to radioactive decay and all the heat lost to conduction. This was done simply by choosing reasonable distributions and concentrations of radioactive elements that yielded a balance between generation and loss and preserved the observed geothermal gradient. As new knowledge about mantle convection and the early history of the Earth accumulated, these models were changed to account for the new findings. There is as yet no definitive thermal model for the Earth, and it is absurd to expect that any such model can be used to determine the Earth's age. Thus, the supposed determination of the Earth's age from thermal calculations by Slusher and Gamwell (118) is totally without merit.

ACCUMULATION OF OOZE ON THE SEA FLOOR
(Table 10, no. 41)

Morris and Parker (97) list an age of the Earth of 5 million years based on the accumulation of calcareous ooze on the sea floor. The reference for this age is a report by Ewing and others (45)[16]. The report by Ewing and his coworkers describes a study of the sediment distribution on the Mid-Atlantic Ridge. They found that the sediment there is 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 report was published before the theory of plate tectonics and sea-floor spreading was formulated, tested, and confirmed. We now know that the midoceanic 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 coworkers is about right for that part of the ridge surveyed by them. Note that Ewing and his coworkers did not calculate an age for the Earth, nor did they produce or describe any data with which such a calculation could be made.

FORMATION OF ^{14}C ON METEORITES

Morris (93, 95) lists an "indicated age of Earth" of 100,000 years from "formation of carbon-14 on meteorites"; he references a report by Boeckl (18). Boeckl's report, however, was about tektites, not meteorites. Tektites are small globules of glass whose origin has been the subject of much debate but is now thought to be from meteoritic impacts on the Earth. Boeckl (18) was attempting to establish a cosmic-ray-exposure-age for these objects to determine their residence time in space. To do so, he assumed a terrestrial age for the tektites of 10,000 years to make his calculations. Boeckl did not calculate an age for the Earth, nor did he produce any data that could be used to do so; Morris (93, 95) even has the number wrong. It is interesting to note that this "age" does not appear in the recent list of Morris and Parker (97) (Table 10), and so perhaps even they realize its absurdity. [10] "Evolutionist" is a term used by creationists to include all scientists who disagree with them.

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

[12] Barnes (13) asserts that this record is unreliable, but he is wrong again. I have refuted Barnes' claim on this matter in detail in another paper (33).

[13] ^{4}He comes from the decay of uranium and thorium in rocks, whereas ^{3}He is primordial. Both are "produced" by escaping from the crust and mantle into the atmosphere.

[14] Remember that radioactive decay is exponential, so in calculating back to the original amount of plutonium, the quantity doubles every 80 million years.

[15] It is curious that Barnes does so. Lord Kelvin thought that the Earth was millions of years old, a view contrary to that of Barnes and his creationist colleagues (Table 9).

[16] Morris and Parker cite the Bulletin of the Geophysical Society of America, but there is no such organization; it is the Geological Society of America.

[‡] Note by Jon Fleming, 2005: Dalrymple's figure for the area of the Moon is four times larger than it should be; apparently someone used the diameter instead of the radius in the area calculation. The final result, a 4.1 cm thick layer on the Moon, is not affected by this error. Since his area of the Earth (5.5×10^{15} ft^2) is correct, his yearly influx per square centimeter on the Moon (2×10^9 g/cm^2/year) is also correct.
$[2\times10^9$ g/cm^2/year$\times4.55\times10^9$ years$]/(2.24$ g/cm$^3) = 4.1$ cm

SUMMARY

Radiometric dating methods provide a reliable means of determining the ages of critical points in geologic and planetary history, including the age of the Earth, the Moon, and meteorites. That the age of the Earth is billions of years is virtually beyond question because it is supported by a wide variety of independently determined scientific evidence which indicates that the Earth is 4.5 to 4.6 billion years old. Scientists are continually refining this age, but it is highly unlikely that it will change in the future by more than a few percent. In the past, the age of the Earth was the subject of much dispute, but the past few decades have 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 geologic time scale (Figure 1), which originally was constructed on the basis of stratigraphic and faunal succession, before the development of modern isotopic dating techniques. Although radiometric dating has allowed scientists to assign ages and to establish the length of the various eras, periods, and epochs, the relative order of these geologic time units has remained unchanged. This is powerful proof that both the dating techniques and the paleontologic and stratigraphic principles on which the time scale was originally based are sound.

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. There are more than 100,000 radiometric ages in the scientific literature that date rock formations and geologic events ranging in age from Holocene to earliest Precambrian. These data and all the accumulated knowledge from the science of geology show conclusively that the Earth we now see is the result of natural processes operating over vast periods and not the product of one or two worldwide catastrophic events.

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 one year during a worldwide flood about 7000 years ago — are demonstrably wrong. There is absolutely no scientific evidence to support these tenets and no scientific grounds for seriously considering "scientific" creationism, as described by Morris (92, 95), Kofahl and Segraves (77), Gish and others (54), and Morris and Parker (97) as a valid scientific theory. Indeed, most of the "research" presented in these publications consists of quoting each other's mistakes.

Moreover, creationists' criticisms of geologic principles in general and of radiometric dating in particular are invalid. Examined objectively, these criticisms invariably turn out to be based on obsolete or nonexistent data, misrepresentations of the scientific evidence, and incomplete, erroneous, or superficial understanding of the methods.

Creationist authors claim that there is scientific evidence for a very young Earth, but their reasoning is invariably flawed by false initial assumptions and a total disregard for the scientific evidence concerning the history of the Earth, its geology, its physics, and its chemistry. Their calculations are meaningless and cannot be taken seriously.

“Scientific” creationism does not provide any rational basis for meaningful scientific investigations of the Earth, the Solar System, or the universe. To accept or even take seriously the tenets of “scientific” creationism requires total abandonment of the results of two centuries of scientific investigations and of the principles of objectivity, rationality, and open-minded inquiry that are fundamental to science.

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Addendum: Derivation of the Neutron Reaction Correction Equation[†]

Jon Fleming has added this section in 2005. The purpose is to show the derivation of Cook's "correction" equation and how non-equal cross-sections affect the result. It is based on two major premises, both of which are almost certainly false:

1. There is no primordial lead in the samples under consideration; all lead was created by radioactive decay and/or neutron capture.

2. The neutron flux was sufficient to create all the ^{208}Pb in the samples, since the ^{208}Pb could not have come from the decay of ^{232}Th (which would leave at least a little residual ^{232}Th in the samples today).

Recall the neutron-capture reaction series presented in the main text:

$$^{206}Pb \xrightarrow{(n,\gamma)} {}^{207}Pb \xrightarrow{(n,\gamma)} {}^{208}Pb$$

We'll move from simple to more complex; starting with the end of the chain, then considering the beginning of the chain, and finally looking at the middle of the chain.

Since we "know" that all the ^{208}Pb was generated by neutron capture, using $C_{207\rightarrow 208}$ to indicate the cross section for converting ^{207}Pb to ^{208}Pb by neutron capture, using N to denote the neutron flux and using $^{208}Pb_{measured}$ to denote the measured amount of ^{208}Pb in the sample today:

$$^{208}Pb_{Measured} = C_{207\rightarrow 208} \times N \times {}^{207}Pb_{Measured} \qquad (1)$$

Or, solving for N:

$$N = \frac{^{208}Pb_{Measured}}{C_{207\rightarrow 208} \times {}^{207}Pb_{Measured}} \qquad (2)$$

Next we move to the beginning of the chain. Here there is one mechanism creating ^{206}Pb (radioactive decay of ^{238}U) and another mechanism destroying ^{206}Pb (neutron capture). Therefore the measured amount of ^{206}Pb today is *less than* the amount created from decay of ^{238}U. Using $^{206}Pb_{Radiogenic}$ as the ^{206}Pb that was generated from radioactive decay and should be used in the determination of age; $^{206}Pb_{Measured}$ as the ^{206}Pb that was actually measured in the sample "today"; and $^{206}Pb_{Converted}$ as the ^{206}Pb that was generated from radioactive decay *and then was converted to ^{207}Pb by neutron capture*:

$$^{206}Pb_{Radiogenic} = {}^{206}Pb_{Measured} + {}^{206}Pb_{Converted} \qquad (3)$$

$^{206}Pb_{Converted}$ is, of course, the amount of ^{206}Pb measured times a conversion factor that is the product of the cross section (for converting ^{206}Pb to ^{207}Pb by neutron capture) and the total neutron flux. Since the ^{206}Pb and ^{207}Pb were in close proximity, the total neutron flux N is the same for both. Calling the cross section $C_{206\rightarrow 207}$:

$$^{206}Pb_{Radiogenic} = {}^{206}Pb_{Measured} + C_{206\rightarrow\, 207} \times N \times {}^{206}Pb_{Measured} \qquad (4)$$

Since N is the same for both ^{206}Pb and ^{207}Pb, we can substitute the right-hand side of equation (2) for the "N" term in equation (4):

$$^{206}Pb_{Radiogenic} = {}^{206}Pb_{Measured} + \frac{C_{206\rightarrow\, 207} \times {}^{208}Pb_{Measured}}{C_{207\rightarrow\, 208} \times {}^{207}Pb_{Measured}} \times {}^{206}Pb_{Measured} \qquad (5)$$

Now we consider the middle of the neutron capture series, the amount of ^{207}Pb generated from radioactive decay, $^{207}Pb_{Radiogenic}$, which should be used in the calculation of age. Here two mechanisms are creating ^{207}Pb (radioactive decay of ^{235}U and neutron capture of ^{206}Pb) and one mechanism is destroying ^{207}Pb (neutron capture creating ^{208}Pb).

$^{207}Pb_{Radiogenic}$ is the measured amount $^{207}Pb_{Measured}$ **plus** the amount of ^{207}Pb that was generated by radioactive decay *but then was converted to ^{208}Pb by neutron capture* (which in turn is equal to the amount of $^{208}Pb_{Measured}$ since we "know" that all the ^{208}Pb came from a one-to-one conversion of ^{207}Pb) and then **minus** the amount of ^{207}Pb that was generated from ^{206}Pb by neutron capture rather than radioactive decay (which in turn is the second term of the right-hand side of equation (5)):

$$^{207}Pb_{Radiogenic} = {}^{207}Pb_{Measured} + {}^{208}Pb_{Measured} - \frac{C_{206\rightarrow\, 207} \times {}^{208}Pb_{Measured}}{C_{207\rightarrow\, 208} \times {}^{207}Pb_{Measured}} \times {}^{206}Pb_{Measu} \qquad (6)$$

And, finally, dividing equation (5) by equation (6):

$$\frac{^{206}Pb_{Radiogenic}}{^{207}Pb_{Radiogenic}} = \frac{^{206}Pb_{Measured} + \frac{C_{206\rightarrow\, 207} \times {}^{208}Pb_{Measured}}{C_{207\rightarrow\, 208} \times {}^{207}Pb_{Measured}} \times {}^{206}Pb_{Measured}}{^{207}Pb_{Measured} + {}^{208}Pb_{Measured} - \frac{C_{206\rightarrow\, 207} \times {}^{208}Pb_{Measured}}{C_{207\rightarrow\, 208} \times {}^{207}Pb_{Measured}} \times {}^{206}Pb_{Measu}} \qquad (7)$$

which, when $C_{207\rightarrow 208} = C_{206\rightarrow 207}$ (as Cook assumed), reduces to the equation given in the main text except for the way that the Pb terms are grouped in the last term of both the numerator and denominator:

$$\frac{^{206}Pb_{Radiogenic}}{^{207}Pb_{Radiogenic}} = \frac{^{206}Pb_{Measured} + \frac{^{208}Pb_{Measured}}{^{207}Pb_{Measured}} \times {}^{206}Pb_{Measured}}{^{207}Pb_{Measured} + {}^{208}Pb_{Measured} - \frac{^{208}Pb_{Measured}}{^{207}Pb_{Measured}} \times {}^{206}Pb_{Measured}} \qquad (8)$$

For calculating the $^{206}Pb/^{207}Pb$ for the third row of Table 5, using Dalrymple's values for cross sections plugged into equation (7):

$$\left(\frac{^{206}Pb}{^{207}Pb}\right)_c = \frac{94.2 + 0.08 \times \frac{0.03}{0.72} \times \frac{94.2}{5.7}}{5.7 + 0.08 - 0.08 \times \frac{0.03}{0.72} \times \frac{94.2}{5.7}} = 16.46$$

I do not know why my result is slightly (0.5%) different from Dalrymple's 16.38, but the difference is not significant.

Using more recent values for the cross sections:

$$\left(\frac{^{206}Pb}{^{207}Pb}\right)_c = \frac{94.2 + 0.08 \times \frac{0.0266}{0.61} \times \frac{94.2}{5.7}}{5.7 + 0.08 - 0.08 \times \frac{0.0266}{0.61} \times \frac{94.2}{5.7}} = 16.47$$

which is insignificantly different from the other values.

To calculate the age from these “corrected” values of $^{206}Pb/^{207}Pb$, we use the standard equation (which cannot be solved in closed form) for age “t” of a sample (in years) given its $^{206}Pb/^{207}Pb$ ratio, the decay constant of ^{238}U ($\lambda_1 = 1.55125\times10^{-10}$ per year), and the decay constant of ^{235}U ($\lambda_2 = 9.8485\times10^{-10}$ per year) is:

$$\left(\frac{^{207}Pb}{^{206}Pb}\right)_c = 137.88 \times \frac{e^{\lambda_2 \times t} - 1}{e^{\lambda_1 \times t} - 1}$$

(from Dalrymple, G. Brent, “The Age Of the Earth”, Stanford University Press, 1991, page 101. The values of λ_1 and λ_2 are from the same source, page 80. Note that the equation uses $^{207}Pb/^{206}Pb$, the inverse of the lead ratios used in this paper and addendum)

The age equation is easily solved by any of a variety of numerical techniques. For $^{206}Pb/^{207}Pb = 16.46$ the calculated age is 630 million years, and for $^{206}Pb/^{207}Pb = 16.47$ the calculated age is 629 million years. Including the effect of non-equal cross-sections for the neutron capture reactions completely obviates Cook’s conclusion. Neutron capture does not noticeably affect the measurement of ages by $^{206}Pb/^{207}Pb$ ratios.

http://www.talkorigins.org/faqs/dalrymple/contents.html