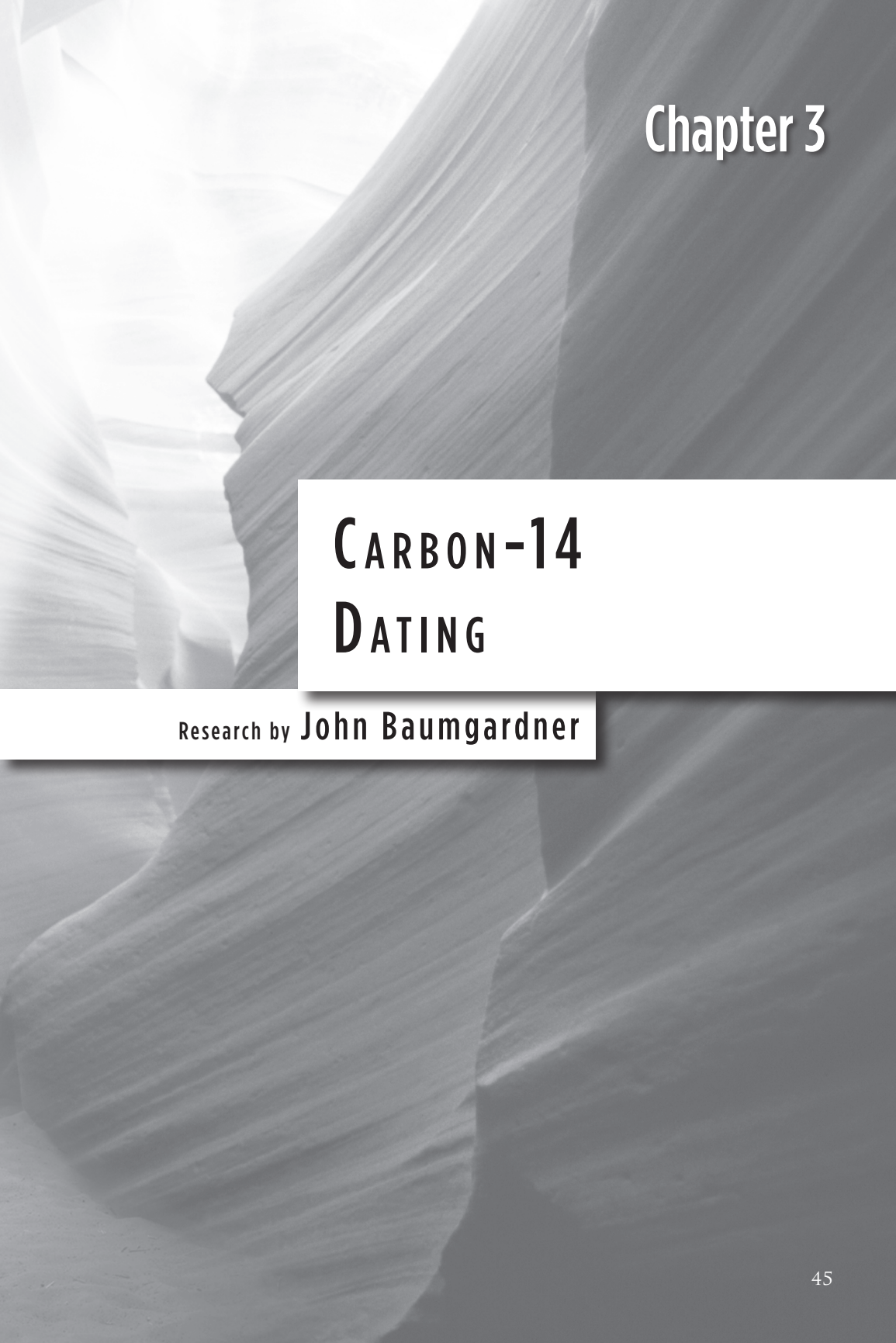

Chapter 3

Carbon-14 Dating

Research by John Baumgardner

How the Method Works

Carbon-14 is by far the most familiar radioisotope dating method. It also is distinguished from the other dating techniques because of its especially short time scale. The half-life of carbon-14 is 5,730 years, compared with millions or billions of years for the radioisotopes used in the other common methods. Also, instead of rock samples, carbon-14 dating usually is applied to the remains of once-living plants and animals — materials such as wood, charcoal, bone, shell, and fossils. The radiocarbon dating method was first introduced by scientist Willard Libby in the 1940s while he worked at the University of Chicago. Libby received the 1960 Nobel Prize in Chemistry for pioneering this important dating technique.

The formation of carbon-14, also called *radiocarbon*, is one effect of cosmic rays that constantly bombard the earth. These high energy particles from space strike molecules of gas in the earth's upper atmosphere and produce free, unattached neutrons. Some of these neutrons then combine with nitrogen-14 atoms to become carbon-14.

$$\text{Nitrogen-14} + \text{Neutron} \rightarrow \text{Carbon-14} + \text{Proton}$$

The resulting carbon-14 atoms drift downward toward the earth's surface. Along the way they combine with oxygen to make carbon dioxide molecules, or CO_2 (Figure 3-1). Living organisms, chiefly vegetation, absorb some of this carbon dioxide from the air. The CO_2 includes the stable, common isotope carbon-12 and also a tiny amount of radioactive carbon-14. There are typically a trillion carbon-12 atoms present for every single carbon-14 atom. An estimated seven kilograms of carbon-14 currently are produced in the upper atmosphere each year. This amounts to about one trillion-trillion (10^{24}) carbon-14 atoms which spread across the earth annually. Both kinds of carbon, C-12 and C-14, become part of the cellulose structure of plants and trees. Both types of carbon also enter the tissues of animals that eat the

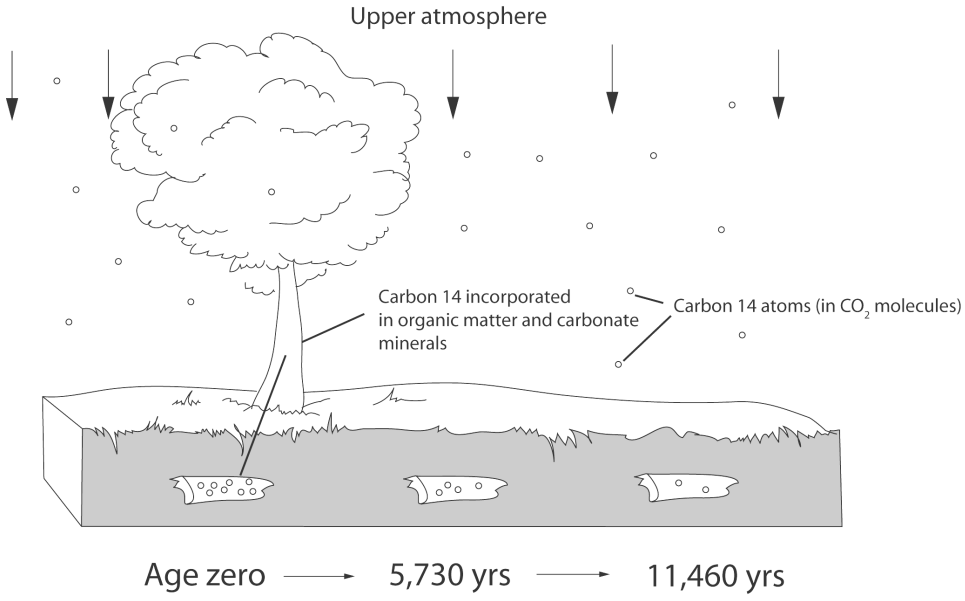

Figure 3-1. Carbon-14 atoms form several miles high in the upper atmosphere. They drift downward toward the earth's surface and combine with oxygen to make carbon dioxide, CO_2. As plants and trees absorb this CO_2, the carbon-14 atoms become a minor part of their fiber. After the vegetation dies, the internal C-14 decays away with a half-life of 5,730 years. The dots in the lower buried wood fragment represent the diminishing number of carbon-14 atoms in a sample.

plants. When the vegetation dies, it no longer absorbs carbon from the air and its trace of accumulated carbon-14 slowly decays back to nitrogen.

$$\text{Carbon-14} \rightarrow \text{Nitrogen-14} + \text{Beta } (\beta)$$

The same is true for an animal when it dies. Carbon dating involves the determination of the amount of carbon-14 remaining in the sample at a later time, usually measured as the ratio of the isotopes C-14/C-12. This value then is compared with the assumed initial carbon-14 content

to estimate the sample age, based on the half-life and other calibration factors. Extreme chemical precision is essential because of the very small amount of carbon-14 present and possible carbon contamination from modern sources.

A Noted Carbon-14 Result

Carbon-14 has found many applications which are of interest to biblical studies. A well-known example concerns the Dead Sea Scrolls, one of the most famous archaeological discoveries of all time. These documents were found by a Bedouin shepherd boy in 1947. Several caves near the Dead Sea held about 800 manuscripts written in Hebrew and Aramaic. The preserved Old Testament manuscripts were found to be very similar to our modern text of the Bible. As a result, some scholars initially concluded that the scrolls must be fairly recent in age, perhaps dating from A.D. 500. However, carbon-14 dating of the linen wrappings, a plant material, showed that the scrolls were much earlier, dating between 150 B.C. and A.D. 70. This is more than 1,000 years older than other known Hebrew biblical texts. The ancient Dead Sea Scrolls demonstrate God's providence in preserving the accuracy of His Word throughout human history. Here and elsewhere in this chapter, carbon-14 is found to be a friend of biblical creation rather than a foe.

The Pervasiveness of Carbon-14

Rocks and fossils containing carbon occur in abundance throughout the earth's strata. Once living organisms now buried in these strata incorporated some carbon-14 within themselves while they were alive. For earth materials classified as ancient, all of this original C-14 content should be completely decayed away. For example, after ten half-lives of decay, any radioactive material has only 0.1 percent remaining of its original content. This small percentage results from multiplying the fraction ½ by itself ten times over. For carbon-14,

this length of time, ten half-lives, is 57,300 years. If the elapsed time is extended still longer to 17–18 half-lives, corresponding to about 100,000 years, carbon-14 decays to an entirely negligible level that is undetectable by current measurement techniques. To express this in another way, any carbon-containing materials that are truly older than 100,000 years should be "carbon-14 dead" with C-14 levels below detection limits. This fact gives rise to a major challenge to the long age assumption for rocks and fossils. In recent years, readily detectable amounts of carbon-14 have been the rule rather than the exception. This is true for samples from throughout the fossil-bearing parts of the geologic record with presumed ages extending to hundreds of millions of years. The unexpected carbon-14 was initially assumed to be a result of contamination, most likely from the experimental counting procedures, but as this problem was aggressively explored, it was realized that most of the carbon-14 was inherent to the samples being measured.

Several creation scientists have previously explored carbon-14 dating, including Melvin Cook, Robert Whitelaw, Robert H. Brown, and John Woodmorappe. Also, Paul Giem conducted an extensive survey of the radiocarbon literature from the 1980s and 1990s. He found more than 70 published reports of significant amounts of carbon-14 detected in "ancient" organic samples. A further RATE review of the radiocarbon literature found many additional examples. These include carbon-14 in fossils, petrified wood, shells, whale bone, coal, oil, and natural gas. The resident carbon-14 content is also found in inorganic rocks and minerals including marble, graphite, and calcite. These samples are from all around the world and from all depths. The detected carbon-14 atoms simply should not exist in these "ancient" materials.

To understand the significance of this carbon-14 finding, consider a comparison. Suppose an archaeologist investigates an Egyptian mummy. The outer covering is carefully removed to reveal

the ancient, undisturbed interior. As the last wrapping is removed an amazing discovery is made. Inside the mummy is a wind-up clock which is still ticking! Perhaps the mummy is not as old as the archaeologist initially thought. The discovery of carbon-14 in "ancient" samples is just as startling to the conventional radioisotope dating community.

Modern technology has made reliable detection of minute amounts of carbon-14 possible. In the earlier decades, the carbon-14 content in samples was measured by counting the beta radiation emitted from the few C-14 atoms which decayed in a sample during a few hours of monitoring (Table 2-1). This is a statistical process with serious limitations although it is still widely used. Since the late 1970s, a new approach became available called *accelerator mass spectrometry*, or AMS. This method allows the actual counting of individual C-14 atoms without the requirement that they decay. It is this precise AMS technique which detects carbon-14 atoms in samples at lower levels than was possible with the previous beta counting method. AMS measurements carefully eliminate all possible sources of carbon contamination. These include any trace of C-14 which has possibly entered the samples in recent history, or C-14 introduction during sample preparation and analysis. The limit of carbon-14 detection using AMS is about one carbon-14 atom for every 10^{16} stable carbon-12 atoms. This is an amazing sensitivity of one part per ten thousand trillion. It is equivalent to detecting one unique sand grain along a 100 mile-long seashore.

The presence of small amounts of C-14 in practically all carbon-bearing earth materials raises an additional concern for the radiocarbon dating method. In dating experiments, the standard practice is to count C-14 atoms in the sample and also in a "procedural blank" or calibration standard. Many laboratories use Precambrian graphite, purified natural gas, or optical grade calcite for the counting standard. This "blank" is thought to hold no C-14

whatsoever, so any counts recorded with it in place are assumed to come from the surrounding "background." These counts are subtracted from the count for the actual sample. However, we now find that the calibration blank itself may not be carbon-14–free. The counts obtained using this blank are not all coming from the background environment after all. Therefore, these counts should not be subtracted out during the sample dating procedure. The result of this incorrect counting is that many samples in past years have been carbon-14 dated older than they actually are.

RATE Carbon-14 Research on Coal

Coal is an abundant fossil fuel consisting of buried vegetation, almost entirely composed of carbon. It is usually assumed to have formed in the distant geologic past in a swamp environment. Much coal is dated to the Pennsylvanian Period, about 300 million years ago. This is also called the late Carboniferous Period or the Age of Coal. Let us explore where geologists place the Pennsylvanian Period in earth history. Table 3-1 shows the standard geologic time scale. This is the assumed chronological sequence of rock strata, portions of which are found worldwide. The dates shown are loosely based on radioisotope results from volcanic ash and magma flows which intrude sedimentary rock layers. Notice that the Precambrian base of the time scale spans nearly 90 percent of the total assumed earth history. Above the Precambrian are fossil-bearing rock layers named Paleozoic (ancient life), Mesozoic (middle life), and Cenozoic (recent life). These three eras together are called the *Phanerozoic Eon*. This means "visible life," so named because these layers contain abundant visible fossils, unlike the Precambrian. The eras are further divided into periods such as Pennsylvanian. Table 3-1 shows this period covering the time span from 323–290 million years ago. These figures, revised slightly every few years, are taken from a 1998 Geological Society of America publication.

Table 3-1. A summary of the geologic eras, example fossil organisms, periods, and conventional time spans. The ages are taken from the Geological Society of America as of 1998. These vast time scales are not accepted by the RATE team.

Era	Representative Organisms	Period	Millions of Years Ago
Cenozoic "Recent life"	Mammals	Quaternary Tertiary	1.8–present 65–1.8
Mesozoic "Middle life"	Reptiles	Cretaceous Jurassic Triassic	144–65 206–144 248–206
Paleozoic "Ancient life"	Amphibians	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian	290–248 323–290 354–323 417–354 443–417 490–443 543–490
Proterozoic Archean (Together called Precambrian)	Bacteria, Algae	Several	4,600–543

If Pennsylvanian coal is truly hundreds of millions of years old, then no remaining carbon-14 whatsoever should be present within it. However, since the AMS method came into widespread use in the 1980s, there have been ongoing reports in the literature of traces of radiocarbon detected in coal. The RATE group further explored this possibility. Ten coal samples were obtained from the U.S. Department of Energy Coal Sample Bank, a storage site which is maintained at Pennsylvania State University. These samples were collected from major coalfields across the United States for

comparative research studies. The coals are carefully preserved at low temperature in an environment of argon gas. The particular RATE samples, 300 grams each, were chosen from across the geologic span of time. They cover the Paleozoic, Mesozoic, and Cenozoic eras. These samples were analyzed for their C-14 content using the modern AMS method. The work was contracted out to one of the foremost carbon-14 laboratories in the world. Four AMS carbon-14 measurements were made for each sample and the results were averaged. As always, extreme care was taken to eliminate all possible sources of carbon-14 contamination.

Table 3-2 summarizes the RATE results for the coal samples. Also listed are the locations of the coal beds and their assumed geologic ages. The right column shows that a residue of carbon-14 atoms was found in all ten samples. The carbon-14 content is measured in percent modern carbon, or pMC. First, one measures the ratio of C-14 to the total carbon present in the coal, mostly carbon-12. Then this ratio is expressed as a percentage of the same C-14/C-12 ratio existing in the present-day atmosphere. The amounts of C-14 in coal are found to average 0.25 percent of that in the atmosphere today.

The carbon-14 data for coal in the table shows a ± uncertainty or error margin for each measurement. Most of the data in the other tables of this book also show ± values. This does not mean that the true value is necessarily sandwiched between these boundaries. For example, the first entry in Table 3-2 shows a carbon-14 content of 0.30 ± 0.03 pMC, which gives a range between 0.27 and 0.33. This is a statistical result and is equal to a total spread of two standard deviations. Standard deviation measures the variation of data from the mean or average. Standard deviation is often identified by the Greek letter sigma, σ. Thus the coal sample value is $0.30 \pm 1\sigma$ pMC. Probability theory shows that if one were to make a large number of similar measurements, 68.3 percent of them would fall within $\pm 1\sigma$ of the center value. For the particular coal sample then, 68.3 percent of repeated measurements would fall

Table 3-2. The carbon-14 content for ten RATE samples of coal. The columns show the coal locations and their conventional geologic ages. The samples include Paleozoic, Mesozoic, and Cenozoic coals. The right column gives the quantity of measured carbon-14 in each sample in percent modern carbon, pMC, defined in the text. The laboratory subtracted a "background" of 0.08 pMC to obtain these values.

Coal Location and Geologic Era	Coal Seam	Conventional Geologic Age (Millions of Years)	C-14/C-12 (pMC ±1σ)
Cenozoic			
Texas	Bottom	34–55	0.30 ± 0.03
North Dakota	Beulah	34–55	0.20 ± 0.02
Montana	Pust	34–55	0.27 ± 0.02
Mesozoic			
Utah	Lower Sunnyside	65–145	0.35 ± 0.03
Utah	Blind Canyon	65–145	0.10 ± 0.03
Arizona	Green	65–145	0.18 ± 0.02
Paleozoic			
Kentucky	Kentucky #9	300–311	0.46 ± 0.03
Pennsylvania	Lykens Valley #2	300–311	0.13 ± 0.02
Pennsylvania	Pittsburgh	300–311	0.19 ± 0.02
Illinois	Illinois #6	300–311	0.29 ± 0.03
Average percent modern carbon for the ten coal samples is 0.247 ± 0.025			

between 0.27 and 0.33 pMC. This uncertainty in value is often due to the limits of the analytical chemistry and electronic equipment used in the measurement. It is important to keep this statistical definition in mind when radioisotope ages are given in future chapters. An alternate range of ± 2 σ is often used to describe uncertainty. This ± 2σ range gives a 95.4 percent chance of repeatability. For example, looking ahead to Table 6-1, which uses the ± 2σ convention, the entry for Grand Canyon sample MT-3 gives a conventional age of 535 ± 48 million

years. This does not imply the actual age of the rock must lie within the range 487–583 million years. Instead it means that, given a large group of equal-age, cogenetic samples, the ages measured in the laboratory will fall within this range 95.4 percent of the time, regardless of whether the calculated ages are right or wrong.

RATE Carbon-14 Research on Diamonds

Diamonds are a crystalline form of pure carbon. They are thought to originate in the upper mantle at a depth of more than 150 kilometers (90 miles), where both pressure and temperature are extreme. At a later time, the diamonds may be carried to the earth's surface by upward-moving magma. There are indications that, in the past, some of this high-pressure, gas-charged magma surged upward at supersonic speeds of hundreds of miles per hour. This rising magma collected debris from the fractured rock strata it passed through as it burst upward and erupted at the surface. After cooling occurred, some of this hardened magma became a type of rock called *kimberlite* or *blue ground*. Another rock variety called *lamproite* may also crystallize from the cooling magma. The result is a long column called a *diamond pipe*. It spreads outward and becomes wider at the earth's surface, giving an underground shape somewhat like a giant carrot, hundreds of feet in diameter. During its formation, the pipe acts as a high-speed elevator, carrying dispersed diamonds to the surface. The diamonds are mined from these pipes in such locations as Australia, Brazil, Canada, Russia, and South Africa. Some of the largest excavations on earth are mined-out diamond pipes. Other pipes are tapped into from underground mines. Diamonds are also occasionally found in gravels called *placer* or *alluvial deposits*. These gems collect downstream from where kimberlite pipes once spewed out diamond-rich debris over the surrounding terrain.

The RATE team realized that natural diamonds would provide an extreme test of the pervasive presence of C-14 in earth materials.

Diamonds are typically assumed to be many millions of years old, if not billions. This vast age is based on the radioisotope dating of inclusions sometimes found inside diamonds. Diamond also is the hardest natural substance on earth. It therefore is very resistant to chemical alteration or contamination. The melting temperature of diamond is about 4,000°C, much higher than common metals. The carbon within diamond is assumed to have remained locked away from any exchange with the atmosphere since early in earth's history.

Twelve diamond samples were analyzed for possible carbon-14 content. These specimens originated from West and South Africa. They were about 0.25 carat in weight, or 50 milligrams each. The diamonds averaged two millimeters in diameter, about the thickness of two dimes. Unfortunately the AMS analysis for carbon-14 requires that the diamonds be destroyed. They are first crushed to very small chips, then rigorously and carefully cleaned, and finally burned, converting them to carbon dioxide. This gas is then condensed to a speck of graphite which the AMS instrument analyzes. In this process, one should not picture beautiful diamonds being hammered to dust! The raw, uncut diamonds analyzed by RATE have a rounded, glassy appearance. They are of industrial grade rather than gem quality, and are not excessively expensive.

The carbon-14 content measured for the 12 RATE diamonds is shown in Table 3-3. Similar to the earlier results for coal, all 12 diamond samples have detectable carbon-14 content, once again measured in percent modern carbon, pMC. The average C-14 content in the diamonds is 0.09 percent that of modern carbon, about one-third that found in coal. As far as we can determine, this RATE research marks the first time that carbon-14 measurements have been made on diamond. The presence of C-14 in "very old" fossils, rocks, coal, and diamond samples is clearly in major conflict with the long-age time scale.

Table 3-3. The carbon-14 content for 12 diamond samples from West and South Africa. The last seven diamond sources in the list are placer deposits found in stream beds. The right column gives the measured carbon-14 content in percent modern carbon, pMC, as defined in the text. The laboratory subtracted a "background" of 0.08 pMC to obtain these values.

Country of Origin	Diamond Location	C-14/C-12 (pMC ±1σ)
Botswana, South-Central Africa	Orapa mine	0.06 ± 0.03
	Orapa mine	0.03 ± 0.03
	Lethakane mine	0.04 ± 0.03
	Lethakane mine	0.07 ± 0.02
South Africa	Kimberley mine	0.02 ± 0.03
Guinea, West Africa	Kankan placer	0.03 ± 0.03
Namibia, Southwest Africa	Placer deposits	0.31 ± 0.02
(Six diamond samples)		0.17 ± 0.02
		0.09 ± 0.02
		0.13 ± 0.03
		0.04 ± 0.02
		0.07 ± 0.02
Average percent modern carbon for the 12 diamonds is 0.09 ± 0.025		

Attempts to Explain Traces of C-14

Is there any way that new carbon-14 atoms could possibly enter and contaminate materials which are truly ancient? Three suggestions will be evaluated here. The first idea is that either the earth's atmosphere or moving groundwater somehow supplies old samples with new C-14 atoms. If true, this migration of carbon-14 would likely be an ongoing process throughout history. To maintain traces of radiocarbon in ancient material, the carbon content would have to be replaced many times over since carbon-14 is radioactive and does not last. The extreme variety in the thickness, depth, and porosity of the earth's rock layers would surely lead to great variation in C-14 contamination by air or water if this does indeed occur. However, the

measured traces of C-14 are fairly uniform throughout the rock strata of the earth. Large-scale contamination of the earth's crustal rocks with carbon-14 from the environment is therefore not a reasonable explanation.

The second suggestion involves nuclear reactions in which outside neutrons enter samples and convert either nitrogen-14 or carbon-13 atoms directly to carbon-14. Such reactions can indeed occur, however, calculations show that the resulting C-14 amounts are several thousand times less than the range actually measured.

The third suggestion concerns heavy radioactive isotopes which exist in trace amounts in some samples. These include radium, thorium, and uranium atoms which can decay in several possible ways. A very small fraction of these decays produces carbon-14 atoms. In the case of radium-223, for example, somewhat less than one out of a billion decays produces a carbon-14 nucleus instead of the usual alpha particle. In this and every other case of radioactive decay, the C-14 production remains far below the amounts observed in diamonds. In fact, the generation of carbon-14 by the decay of heavy nuclei results in an amount at least 100,000 times less than the actual C-14 found in samples.

None of the three suggestions can sustain an ancient age while adequately explaining the presence of carbon-14 throughout the earth's crust. The conclusion is that the pervasive presence of C-14 is strong evidence for a youthful earth.

Interpretation of the Carbon-14 Data

How might the carbon-14 findings fit the young-earth view? One intriguing possibility involves the rock strata laid down by the global flood of Noah's day. During the pre-Flood centuries, the C-14 component of carbon was distributed uniformly throughout the earth's vegetation. This *biomass* then was rapidly buried and fossilized during the Flood which occurred about 4,500 years ago. The worldwide burial would lead to the fairly uniform traces of carbon-14 which are found

throughout the earth's strata, no matter what depth of rock is tested. The entire Phanerozoic Eon encompassing the Paleozoic, Mesozoic, and Cenozoic Eras is considered by many creationists to be Flood-deposited rock.

The carbon-14 content of coal, diamonds, and many other earth materials varies between 0.1 and 0.5 percent modern carbon, pMC. These measured numbers translate into carbon-14 ages between 44,000 and 57,000 years based on several assumptions. Such ages are dramatically younger than their normally accepted ages, typically hundreds of millions of years. The RATE team concludes that a key assumption used in obtaining these carbon-14 ages is not correct because the ratio of carbon-14 to total carbon was almost certainly less during pre-Flood times than it is today. We know this from the great reservoir of fossil fuels which were buried during the Flood. This large biomass would have diluted the C-14 in the pre-Flood world to give a very low ratio of C-14/C-12 compared with the present world. The total amount of carbon found within carbonate rocks and fossil fuels, mostly carbon-12, is at least 100 times greater than that which resides in the total biosphere of living plants and animals today. Taking this pre-Flood carbon distribution into account, the carbon-14 ages for coal and diamonds is reduced to just several thousand years.

Another factor is that a stronger geomagnetic field existed during pre-Flood history than exists at present. This early earth magnetism would deflect cosmic rays away from the earth more efficiently than today and would diminish the historical production of carbon-14. Together, these factors can easily decrease the calculated carbon-14 dates of coal and diamond samples tenfold, from 50,000 to just 5,000 years, a value consistent with Flood history. The carbon-14 results from fossil materials cannot pin down biblical dates more precisely, because of the uncertainty in the actual amount of C-14 existing in the pre-Flood world.

There is another complementary creationist explanation for the presence of carbon-14 in earth materials. Some of the measured C-14 may be *primordial*, having been present in the earth from the beginning of time. In the young-earth view, the creation took place just a few thousand years ago. With the passing of time since creation equal to about one C-14 half-life, or 5,730 years, a measurable component of original C-14 would still remain.

Accelerated Nuclear Decay

There is one final possible explanation for the carbon-14 residue found in earth materials. It was shown earlier in this chapter that the decay of heavy isotopes is incapable of producing the observed amounts of carbon-14, but this is only true at today's rates of disintegration. If nuclear decay was greatly accelerated in the past then substantial carbon-14 might have formed as a result. Alpha particles produced by uranium decay, for example, can interact with common elements in rocks such as oxygen, silicon, aluminum, and magnesium. As a result, neutrons are produced. These neutrons, in turn, can interact with underground nitrogen-14 and carbon-13 atoms to produce carbon-14. This could occur in both organic and mineral samples. The unexpected carbon-14 findings may be an indication of accelerated decay events in the past. The RATE team defines accelerated decay as millions of years' worth of nuclear decay, at present rates, taking place very quickly, perhaps in just days. Another way of describing accelerated decay is a temporary, extreme reduction in nuclear half-lives.

The carbon-14 content of the placer diamonds shows considerable variation (Table 3-3). One placer sample in particular has a percent modern carbon value of 0.31, higher than the other diamond samples measured. This suggests that some placer diamonds may have experienced intense nuclear reactions which produced their internal carbon-14 atoms. Perhaps the geological setting of these surface

diamonds may have exposed them to the full effects of accelerated nuclear decay.

Since radiocarbon is still measured in samples today, the carbon-14 itself obviously did not completely decay away in the proposed acceleration process. The sped-up decay may well have depended on the particular half-lives involved. For example, suppose that all isotopes experienced a rapid 8 percent decay. Then uranium-238 with a 4.47 billion year half-life would undergo 540 million years of decay. An 8 percent decay of carbon-14 with its much shorter half-life of 5,730 years corresponds to only 690 years. Thus, there would remain a component of carbon-14 in samples which we still measure today. Accelerated nuclear decay certainly was more complicated than this example, and the concept will be further explored in the following chapters.

The RATE scientists are convinced that the popular idea attributed to geologist Charles Lyell from nearly two centuries ago, "The present is the key to the past," is simply not valid for an earth history of millions or billions of years. An alternative interpretation of the carbon-14 data is that the earth experienced a global flood catastrophe which laid down most of the rock strata and fossils. Also, many rates of change were accelerated in the recent past including sedimentary rock formation, erosion rates, and radioactive decay. Whatever the source of the carbon-14, its presence in nearly every sample tested worldwide is a strong challenge to an ancient age. Carbon-14 data is now firmly on the side of the young-earth view of history.

Further Study

There is another radioactive isotope similar to carbon-14 which might provide valuable insight on the earth's age. This isotope is beryllium-10, Be-10, with a half-life of 1.52 million years. Somewhat similar to carbon-14, it results when cosmic rays collide with nitrogen and oxygen atoms in the earth's upper atmosphere. Fragmentation

or *spallation* of the oxygen and nitrogen results in the formation of light-weight atoms including lithium, beryllium, and boron. This transformation also occurs on the outside surface of minerals which lie exposed on the ground. A technique called *cosmogenic exposure dating* is used to date these minerals. The concentration of beryllium-10 is taken as a measure of their total exposure time.

In deeply buried rocks, assumed to be ancient, any originally accumulated beryllium-10 atoms should be depleted by nuclear decay. However, there is mention in the geologic literature of Be-10 detected in these deep rocks (Faure and Mensing, 2005). This unexpected presence of Be-10 is very similar to the discovery of carbon-14 in samples. A worthwhile research program would entail the search for beryllium-10 in buried rock samples, perhaps obtained from drill cores. Any existing Be-10 from these lower levels would give additional evidence that the rocks, and the earth itself, are much younger than the standard geologic time scale implies.