Chapter 2

Young Helium Diffusion Age of Zircons Supports Accelerated Nuclear Decay

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Abstract. Experiments sponsored by RATE show that helium leakage deflates long half-life radioisotopic ages. In 1982 Robert Gentry found amazingly high retentions of nuclear-decay-generated helium (He) in microscopic zircons ($ZrSiO_4$ crystals) recovered from a borehole in hot Precambrian granitic rock at Fenton Hill, New Mexico. In 2001 RATE contracted with a high-precision laboratory to measure the rate of He diffusion out of the zircons. The measured rates resoundingly confirm a numerical prediction we made based on the reported retentions and a young age. Combining rates and retentions gives a He diffusion age of 6000±2000 (1σ) years. This contradicts the uniformitarian age of 1.5 billion years based on nuclear decay products in the same zircons. These data strongly support our hypothesis of episodes of highly accelerated nuclear decay occurring within thousands of years ago. Such accelerations shrink the radioisotopic "billions of years" down to the 6000-year timescale of the Bible.

In section 13 I discuss, in the light of our diffusion data, one of the problems for the accelerated decay hypothesis, disposal of excess radiogenic heat. Appendices A–C present details of our experimental data. Appendix D is an extensive answer to a critic of this work.

This chapter combines and updates three publications presented at or in: (1) the Fifth International Conference on Creationism in August 2003, (2) an American Geophysical Union annual meeting in December 2003, and (3) the *Creation Research Society Quarterly* in June 2004. When I say "we" below, I am referring to my co-authors for those papers. They are my three colleagues on the He diffusion project from the RATE steering committee:

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1. Introduction

A significant fraction of the earth's radioactive elements, particularly U and Th, appear to be in the granitic rock of the upper continental crust. In the granites, U and Th tend to be localized inside special minerals such as *zircon* (zirconium silicate, $ZrSiO_4$). Zircon has high hardness, high density, and high melting point, often forming microscopic, stubby, prismatic crystals with dipyramidal terminations (Figure 1), commonly grayish, yellowish, or reddish brown. Atoms of U and Th within cooling magma replace up to 4% of the normal Zr atoms within the lattice structure of zircon as it is crystallizing. In contrast, the products of U and Th decay that are also in the magma do not incorporate themselves into the lattice. In particular, the most common type of lead ions (Pb^{2+}) are too large to fit into the lattice. Thus in a newly formed zircon, the U concentration is much greater than in the magma, while the Pb concentration is much less than in the magma. The radioactive zircon crystals often become embedded in larger crystals, such as mica (particularly biotite), as the magma cools and solidifies.

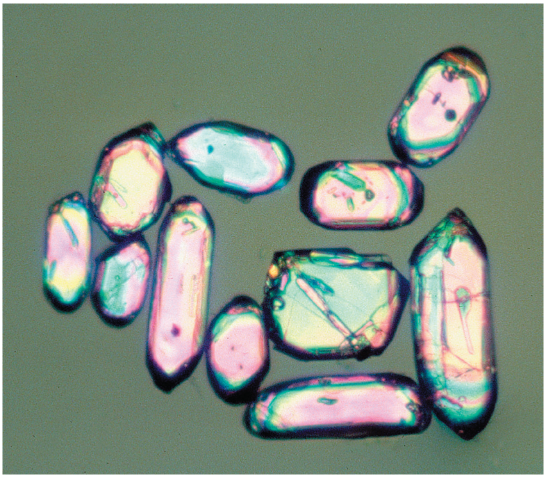

Figure 1. Zircons from the Jemez granodiorite. Photo by R. V. Gentry.

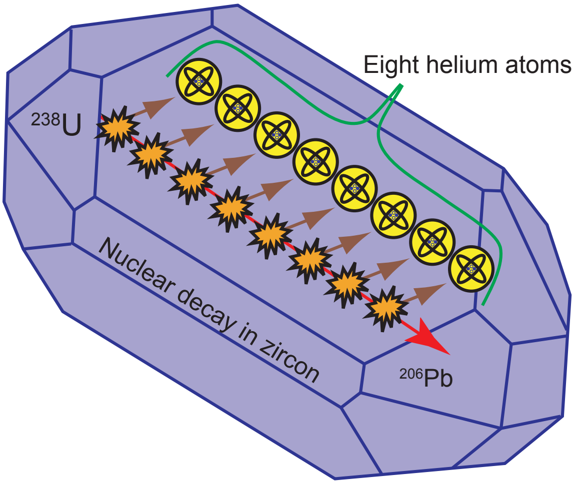

Figure 2. Nuclear decay makes He within zircons.

As the U and Th nuclei in a zircon decay, they produce He (Figure 2). For example, ^{238}U emits eight α-particles as it decays through various intermediate elements to ^{206}Pb. Each α-particle is a ^{4}He nucleus, consisting of two protons and two neutrons. Each explosively expelled ^{4}He nucleus eventually comes to a stop, either within the zircon or in the surrounding material. There it quickly gathers two electrons and becomes a neutral He atom.

Helium is a lightweight, fast-moving atom that does not form chemical bonds with other atoms. It can *diffuse* through solids relatively fast, meaning that He atoms wiggle through the spaces between atoms in a crystal lattice and spread themselves out as far from one another as possible. For the same reason it can leak rapidly through tiny holes and cracks, making it ideal for leak detection in laboratory vacuum systems. The diffusion and leakage rates are so great that believers in the billions of years had expected most of the He produced during the alleged 4.5 billion years of the earth's existence to have worked its way out of the crust and into the earth's atmosphere long ago. In this chapter we argue that, in this case and similar cases, the He has not had enough time (less than 8000 years) to escape from the zircons, much less the crust.

2. The Helium is Still in the Zircons

In the 1970s, geoscientists from Los Alamos National Laboratory began drilling core samples at Fenton Hill, a potential geothermal energy site just west of the volcanic Valles Caldera in the Jemez Mountains near Los Alamos, New Mexico (Figure 3). There, in borehole GT-2, they sampled the granitic Precambrian basement rock, which we will refer to as the Jemez granodiorite. It has an assigned radioisotopic age of 1.50 (± 0.02) billion years, as determined by various methods using the U, Th, and Pb isotopes in the zircons themselves [*Zartman*, 1979]. The depths of the samples varied from near the surface down to 4.3 km,

Figure 3. Drilling rig at Fenton Hill, New Mexico. Photo by Los Alamos National Laboratory.

with *in situ* temperatures from 20°C to 313°C (measurement accuracy of ±1°C [*Laney and Laughlin*, 1981, p. 502, Table 1]). The Los Alamos team sent some of these core samples to Oak Ridge National Laboratory for isotopic analysis.

Most of the zircons were in biotite [*Gentry*, 1995], a black mica common in granitic rock. At Oak Ridge, Robert Gentry, a creationist physicist, crushed the samples (without breaking the much harder zircon grains), extracted a high-density residue (because zircons have a density of 4.7 g/cm^3), and isolated the zircons by microscopic examination, choosing crystals about 50–75 μm long. The zircon masses were typically on the order of a microgram. The Oak Ridge team then heated the zircons to 1000°C in a mass spectrometer and measured the amount of ^{4}He liberated. In 1982 they published the data in *Geophysical Research Letters* [*Gentry et al.*, 1982]. Table 1 details their results, plus two samples ("2002" and "2003") from the same borehole we analyzed in the years 2002 and 2003.

The first column itemizes the samples analyzed. The second and third columns show the depth and temperature of each sample *in situ*. The fourth column shows the volume (at standard temperature and pressure) of He liberated in the laboratory per microgram of zircon.

Table 1. Helium retentions in zircons from the Jemez granodiorite. 1 ncc = 10^{-9} cm^3.

Sample	Depth (m)	Temperature (°C)	Helium * (ncc/μg)	Q/Q_0	Error
0	0	20	8.2	—	—
2002	750	96	~12.1	~0.80	—
1	960	105	8.6	0.58	±0.17
2003	1490	124	6.3	0.42	±0.13
2	2170	151	3.6	0.27	±0.08
3	2900	197	2.8	0.17	±0.05
4	3502	239	0.16	0.012	±0.004
5	3930	277	~0.02	~0.001	—
6	4310	313	~0.02	~0.001	—

* After consulting with Dr. Gentry, we have corrected, in the fourth column, two apparent typographical errors in the corresponding column of his table. One is in the units of the column (which should have been 10^{-9} cc/μg instead of 10^{-8} cc/μg); the other is in sample 4 of that column. The crucial fractions in column five were correctly reported, as we have confirmed with our data.

The fifth column is the ratio of the observed quantity of He Q (total number of He atoms in the crystal) to the calculated quantity Q_0 that the zircons would have accumulated and retained if there had been no diffusion. The Los Alamos team measured the amount of radiogenic Pb in zircons 2.9 km deep in the same borehole and same granodiorite [*Zartman*, 1979], and the Oak Ridge team confirmed those figures with their ion microprobe [*Gentry*, 1995]. Because the various decay chains generate an average of 7.7 He atoms per Pb atom produced, Gentry and his colleagues were able to calculate Q_0 from the amount of Pb in the zircons. In doing so, they compensated for the estimated loss of α-particles emitted from near the edges of the zircons out into the surrounding material.

The Oak Ridge team estimated that uncertainties in calculating Q_0 might limit the accuracy of the ratio Q/Q_0 to ±30%. This is by far the dominant error in the analyses throughout this chapter. We will (very conservatively) regard it as a 1σ random error. Column 6 of the table shows the resulting estimated errors in the ratios.

Samples 1 through 6 came from the granodiorite, but sample zero came from larger zircons in a surface outcrop of an entirely different rock unit. For that rock unit U/Th/Pb information was not available, making an estimate of Q_0 not feasible. Lacking a ratio, we cannot use sample zero in the calculations.

Samples 2002 and 2003 came from the same borehole and same rock unit as did samples 1 through 6, but we acquired the former as core samples from Los Alamos National Laboratory only a few years ago. We sent them to Activation Laboratories in Ontario, Canada, where they extracted biotite and zircons. We did not select sizes of zircons in sample 2002, nor measure their total mass accurately, but we did so for sample 2003. The lengths of the latter were between 50 and 75 μm, and the approximately 1200 selected crystals weighed a total of 216 μg. After extraction, we sent both zircon and biotite samples to our diffusion experimenter (Section 5), where he measured the total quantity of He contained in each sample. We used Gentry's estimate of Q_0 to get our estimate of the fraction retained in sample 2003 (see Section 10 for details). We did the same for sample 2002, though we lacked an accurate measurement of its total mass and so did not accurately know the He liberated per microgram.

Samples 5 and 6 had the same amount of He. Gentry and his colleagues noted that He emerged from those samples in shorter bursts than the other samples, indicating a different distribution of He within those zircons. In Section 7, we will show that the amount of He from sample 5 is just about what would be expected from the trend in the cooler samples. But we allow for the possibility of its error being considerably larger than the cooler samples.

According to the thermal behavior outlined in the next section, we would ordinarily expect that the hotter sample 6 would have much less He than sample 5. The fact that the He content did not decrease suggests that some additional effect may have occurred which limited the outflow of He from the zircon. In Section 7 we suggest a likely explanation.

The above considerations suggest that we can use samples 1 through 5 in a theoretical analysis with ordinary diffusion. We will treat sample 6 as a special case.

Samples 1 through 3 had He retentions of 58, 42, 27, and 17%. The fact that these percentages are high confirms that *a large amount of nuclear decay* did indeed occur in the zircons. Other evidence strongly supports much nuclear decay having occurred in the past [*Humphreys*, 2000, pp. 335–337]. We emphasize this point because many creationists have assumed that "old" radioisotopic ages are merely an artifact of analysis, not really indicating the occurrence of large amounts of nuclear decay. But according to the measured amount of Pb physically present in the zircons, about 1.5 billion years worth—at today's rates—of nuclear decay occurred. Supporting that, sample 1 still retains 58% of all the α-particles (the He) that would have been deposited in the zircon during this decay of U and Th to Pb.

It is the uniformitarian (see Endnote i) assumption of invariant decay rates that leads to the usual conclusion that this much decay required 1.5 billion years. In this chapter we will include the assumption of billions of years of time in the uniformitarian model we construct for diffusion.

Notice that the retention levels decrease as the temperatures increase. That is consistent with ordinary diffusion: a high concentration of He in the zircons diffusing outward into a much lower concentration in the surrounding minerals, and diffusing faster in hotter rock. As the next section shows, diffusion rates increase strongly with temperature.

In later sections, we will show that these large retentions (see Endnote ii) are quite consistent with diffusion taking place over *thousands* of years, not billions of years.

3. How Diffusion Works

If the reader is not very familiar with diffusion and wants to know more, we recommend a very clear little book, **Atomic Migration in Crystals**, written for non-experts [*Girifalco*, 1964]. Figure 4, adapted from that book [*Girifalco*, 1964, p. 39, Figure 23], illustrates how an atom diffuses through a solid crystal lattice of other atoms. Figure 4a shows a He atom initially at position A, surrounded by a cell of lattice

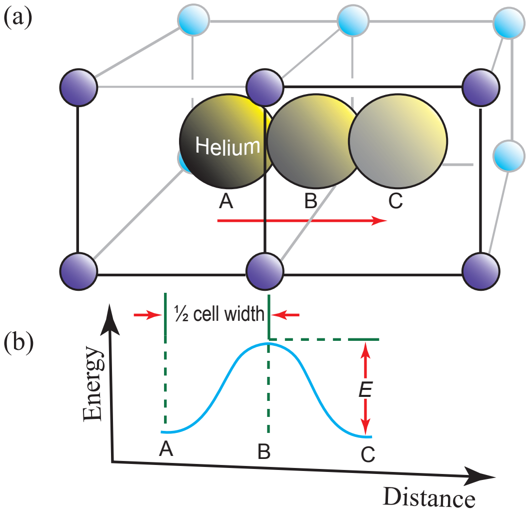

Figure 4. Helium atom moving through a crystal. Usually, lattice cations are smaller than He atoms, but lattice anions are somewhat larger. Here for clarity we show all lattice ions as being small.

atoms. The lattice atoms repel the He atom, tending to confine it to the center of the cell, where the repulsion balances out in all directions. Heat keeps the atoms of the lattice vibrating at its various resonant frequencies. The vibrating atoms continually bump into the He atom from all sides. The higher the temperature, the more vigorous the bumping.

Every now and then, the lattice atoms will bump the He atom hard enough to push it into the "activated" position B, midway between cells. The lattice atoms must give the He enough kinetic energy to overcome the repulsive potential energy barrier between the cells, which we have shown in Figure 4b. This required amount of kinetic energy, E, is called the *activation energy*. If the lattice atoms have given any more energy than E to the He atom, it will not stop at position B. Instead, it will continue on to position C at the center of the adjacent cell. The He atom has thus moved from one cell to the next.

If there is an initially high concentration of He atoms in one part of the crystal, these random motions will eventually spread—that is, diffuse—the He more uniformly though the crystal and out of it. Let us define $C(x, y, z, t)$ as the *concentration*, the number of He atoms per unit volume, at position (x, y, z) at time t. Many textbooks show that when diffusion occurs, the time rate of change of C is proportional to the "sharpness" of the edges of the distribution of He, or more mathematically, proportional to the Laplacian of C, $\nabla^2 C$:

$$\frac{\partial C}{\partial t} = D\nabla^2 C, \quad \text{where}\, \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \qquad \text{(1a, b)}$$

Equation (1a), called the "diffusion equation," occurs frequently in many branches of physics, for example, to describe heat conduction in solids. Specialists in the diffusion of atoms through materials call it "Fick's Second Law of Diffusion." The factor D, the *diffusion coefficient*, or *diffusivity*, has dimensions of cm^2 (or m^2) per second. (Most of the diffusion literature still uses centimeters and calories instead of meters and joules). Very often it turns out that at high temperatures, the diffusion coefficient depends exponentially on the absolute temperature T (degrees Kelvin above absolute zero):

$$D = D_0 \exp\left(-\frac{E_0}{RT}\right) \tag{2}$$

where R is the universal gas constant, 1.986 calories per mole-Kelvin (8.314 J/mol-K). The constant D_0 is independent of temperature. The "intrinsic" activation energy E_0 typically is between 10 and 100 kcal/mol (about 40 and 400 kJ/mol). Section 11 discusses how these quantities are related to the geoscience concept of *closure temperature*, and it shows why the concept is irrelevant to our conclusions.

If the crystal has *defects*, such as vacancies in the crystal lattice, impurities, dislocations, grain boundaries, or damage from radiation, then the diffusion coefficient equation will have a second term related to the defects:

$$D = D_0 \exp\left(-\frac{E_o}{RT}\right) + D_1 \exp\left(\frac{E_1}{RT}\right) \tag{3}$$

The defect parameters (D_1 and E_1) are almost always smaller than the intrinsic parameters (D_0 and E_0):

$$E_1 < E_0, \quad D_1 < D_0 \tag{4}$$

The typical *Arrhenius plot* in Figure 5 shows how the diffusion coefficient D of equation (3) depends on the inverse of the absolute temperature, $1/T$. Because the plot uses a logarithmic scale for D and a linear scale for $1/T$, each term of equation (3) manifests itself as a straight line in the temperature region where it is dominant. (Plotting with T instead of $1/T$ would make the lines curved instead of straight.) The slopes are proportional to the activation energies E_0 and E_1. The intercepts with the vertical axis, where $1/T$ is zero, are the parameters D_0 and D_1.

The intrinsic line has a steep slope and a high intercept, while the defect line has a shallow slope and a low intercept. Starting on the right-hand side of the graph, at low temperatures, let us increase the temperature, moving to the left. When the temperature is high enough, we reach a region, the "knee," where the two terms of equation (3)

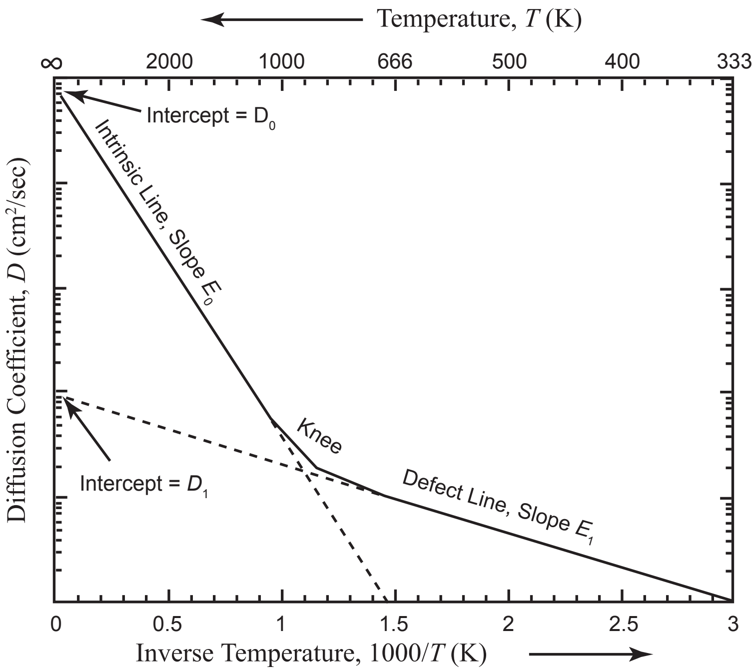

Figure 5. Typical Arrhenius plot.

are about equal. To the left of that region, at high temperatures, the intrinsic properties of the crystal dominate the diffusion. To the right of the knee, at lower temperatures, the defects dominate. Because defects are very common in natural crystals, this two-slope character is typical [*Girifalco*, 1964, pp. 102, 126].

For a given type of mineral, the location of the knee can vary greatly. It depends on the value of D_1, which depends on the amount of defects in the particular crystal. The more defects there are, the higher D_1 is. If we increase the number of defects, the defect line moves upward (keeping its slope constant) on the graph, as Figure 6 illustrates.

In the case of zircons containing radioisotopes, the main cause of defects is radioactivity, so highly radiation-damaged (“metamict”) zircons will have a large value of D_1, causing the defect line to be higher on the graph than for a low-radioactivity zircon.

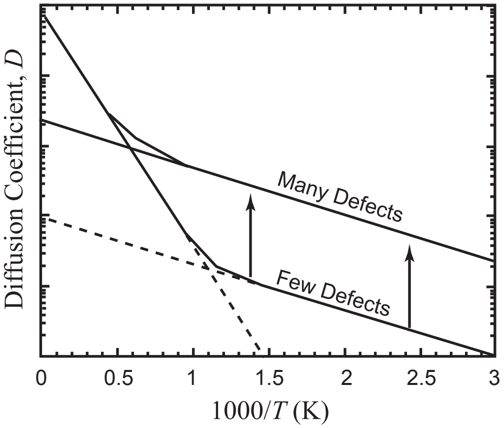

Figure 6. Increasing number of defects slides the defect line upward.

4. I Misunderstood Early Zircon Data

At the beginning of our investigations in 1997, I did not properly understand the only source of He-in-zircon data that was available then, and that influenced the course of the RATE research. My misunderstanding caused us: (a) to think that the main restriction on He outflow from the zircon was not the zircon itself, but rather the biotite surrounding the zircon, and consequently (b) to commission our own experiments. The outcome proved to be very fortunate, because we acquired a much better understanding of the He diffusion *in situ*. Here are more details.

Our initial source of He-in-zircon diffusion data was a 1970 paper by Sh. A. Magomedov, a researcher in Dagestan (then part of the Soviet Union). He published diffusion data for radiogenic Pb and He in highly metamict (radiation-damaged) zircons from the Ural Mountains [*Magomedov*, 1970]. These were the only He-in-zircon diffusion data we could find during an extensive literature search we did in 1999.

Magomedov was mainly interested in Pb diffusion, so he did not list his He data explicitly in a table. Instead he showed them in a small graph, along with data for Pb diffusion and electrical conductivity, σ. His label for the ordinate was not clear to me: "ln(D,σ)." In Western scientific literature “ln” with no further note usually means the *natural* logarithm (base *e*). The common logarithm (base 10) is usually shown as “log.” (That is not always so in some Russian articles, but I did not think of that.) I first assumed Magomedov was reporting $\ln_e D$, which made the resulting diffusion coefficients very high, as the triangles and dotted line near the top of Figure 7 show. The previous RATE book shows that interpretation [*Humphreys*, 2000, p. 347, Figure 6]. Another possibility was that Magomedov was reporting $\ln_e(D/a^2)$, where a is the effective radius of his zircons, about 75 µm. Figure 7 shows (circles and thin solid line near middle) the resulting diffusion rates for that interpretation. In the temperature range of interest to us, the rates are still rather high.

Based on those supposed high rates, I assumed in my first theoretical model [*Humphreys*, 2000, pp. 346–348] that the zircons were a negligible impediment to He outflow, compared to the minerals around

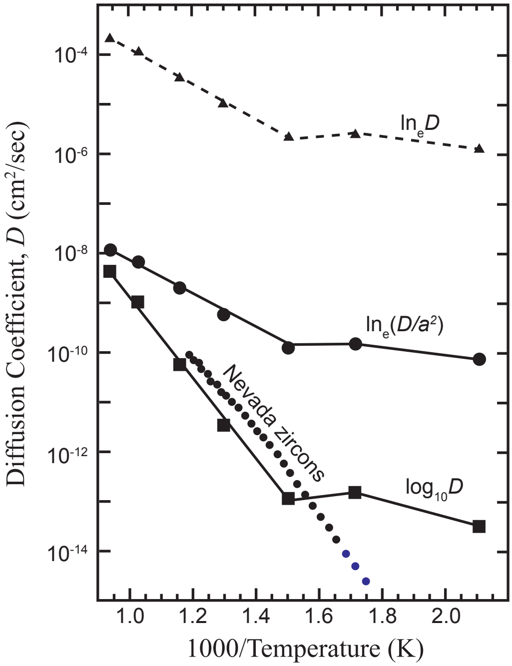

Figure 7. Interpretations of Russian zircon data (hollow symbols and lines) compared with Nevada zircon data (dots). The ordinate is D (not D/a^2)

them, such as the biotite. That made the RATE project concentrate our first experiments on He diffusion not in zircon, but rather in biotite, for which we found no previous measurements in the literature.

But in 2001 we received a preprint of a paper [*Reiners et al.*, 2002] listing new He diffusion data in zircons from several sites in Nevada. Figure 7 shows some of that data (Fish Canyon Tuff sample FCT-1) as a line of solid dots. These data were many orders of magnitude lower than our interpretation of Magomedov's graph. The Russian data would agree with the Nevada data if we re-interpret Magomedov's label as meaning "$\log_{10} D$," the *common* logarithm of D. Figure 7 shows that interpretation near the bottom (squares and thick solid line). We attribute the small difference between the high-slope "intrinsic" parts of the Russian and Nevada data to differences in estimates of effective radius (Section 5). The nearly horizontal part of the Russian data is probably a "defect" line due to much radiation damage (see end of previous section). That part of the Russian data is about two orders of magnitude higher than data from zircons in Nevada and New Mexico (compare D numbers at bottom of Figure 7 with those in Figures 8 and 13). It turns out that the low-temperature "defect" part of the Russian data is about seven orders of magnitude too high to support a uniformitarian interpretation.

The new data and my new interpretation of the old data imply that zircon is a significant impediment to He diffusion, and that we cannot neglect it. In Section 7 of this chapter I report how we changed our theoretical model to account for that fact.

5. Pre-2003 Data for Jemez Granodiorite Minerals

The Nevada zircon data did not extend to low enough temperatures to compare them with the He retentions. Moreover, they were not from the New Mexico site. Measurements of noble gas diffusion in a given type of naturally occurring mineral often show significant differences from site to site, caused by variations in composition and amounts of defects. For that reason it is important to get He diffusion data on zircon and biotite from the same rock unit (the Jemez granodiorite) that was the source of Gentry's samples. Accordingly, in 2001 the RATE project commissioned such experimental studies.

Through a small mining company, Zodiac Minerals and Manufacturing, we contracted with a well-recognized expert on He diffusion measurements in minerals, having many publications related to that field. As we wished, Zodiac did not tell him they were under contract to us, the goals of the project, or the sites of the samples. We have encouraged him to publish his measurements and offered to send him the geologic site information if he does so. Appendices B and C list his data in detail.

We decided to get data on biotites and zircons from the same borehole, GT-2, from which Gentry's zircons came. Los Alamos National Laboratory kindly gave us several GT-2 core samples from a depth of 750 m. That is somewhat shallower than Gentry's samples, but still in the same rock unit. We sent one of them to Activation Laboratories in Ontario, Canada, where they extracted the biotite and zircons. They did not separate the zircons into size groups. They measured the U and Pb isotopes in three of the zircons, getting a U-Pb concordia age of 1439±2 Ma (Appendix A). That is within a few percent of the published age for zircons deeper in the same borehole, 1500±20 Ma [*Zartman*, 1979]. We reserved the rest of the zircons, roughly 0.35 mg, for diffusion measurements.

Then we sent both the biotite and the zircons to our diffusion experimenter. He sieved the biotite sample to get crystals between 75 and 100 μm, but he used all the zircons that Activation Laboratories had extracted, regardless of size. Size of crystals (*effective radius*) is important in converting the raw data into diffusivities. For a description of a typical diffusion experimental apparatus, see an article in *Analytical Chemistry* [*Farley et al.*, 1999]. Our experimenter sent us the raw data in 2002, which is the reason we call the sample "2002" in Table 1.

Figures 8 and 9 are Arrhenius plots of the data we had by early 2002 for zircon and mica, respectively. The zircon data in Figure 8 are from the Jemez granodiorite in New Mexico [from our experimenter, see our Appendix C, Table C1], the Fish Canyon Tuff in Nevada [*Reiners et al.*, 2002], and the Ural Mountains in Russia (re-interpreted from *Magomedov* [1970]). We are assuming their average size was the same

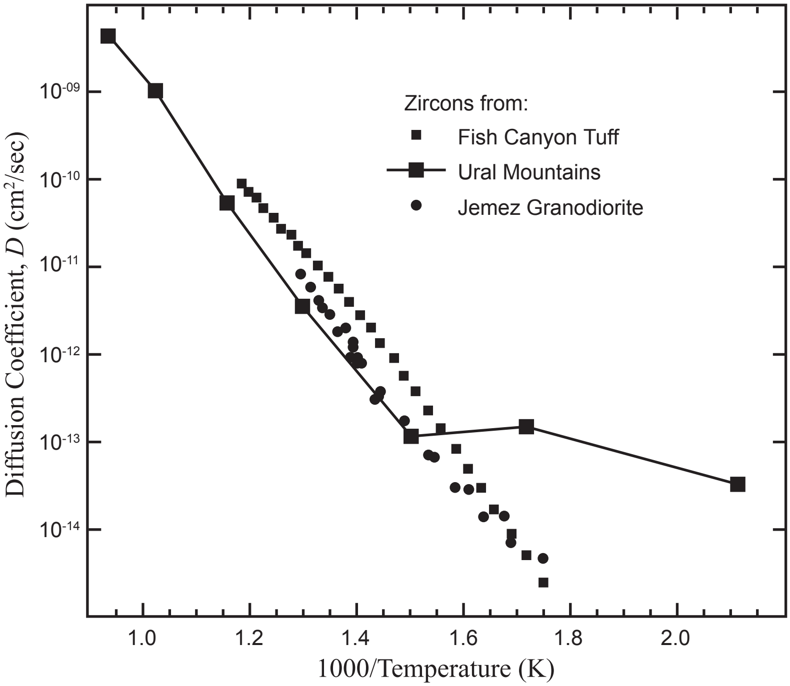

Figure 8. Observed diffusion coefficients in zircons. The ordinate is D (not D/a^2).

as the Nevada zircons (average length ~60 μm, $a \cong 30$ μm, Section 6). The Russian study was for crystals ~150 μm long.

Notice that all the sets of zircon data agree fairly well with each other at high temperatures. At 390°C (abscissa = 1.5), the Russian data have a knee, breaking off to the right into a more horizontal slope for lower temperatures. That implies a high number of defects (see section 4), consistent with the high radiation damage Magomedov reported. The Nevada and New Mexico data (sample 2002) go down to 300°C (abscissa = 1.745) with no strong knee, implying that the data are on the intrinsic part of the curve. Our least-squares linear curve fit [of $\ln(D/a^2)$ from equation (2) versus $1/T$] to these New Mexico (Jemez granodiorite) zircon data gives the following diffusion parameters, and the 1σ error bounds of the fit:

$$E_0 = 34.4 \pm 0.9\,\text{kcal/mol}, \quad \frac{D_0}{a^2} = 3548^{+3100}_{-1700}\,\text{sec}^{-1} \qquad \text{(5a, b)}$$

Figure 9 shows data for two types of mica, biotite and muscovite. The biotite data are from the Jemez granodiorite. Those, and similar data we obtained (see Appendix B) for biotite from the Beartooth amphibolite in Wyoming, are the only data for that mineral we know of. For comparison to the biotite data, we have also included published data for muscovite [*Lippolt and Weigel*, 1988].

The muscovite and biotite data are consistent with each other. In the low temperature range of interest, the New Mexico biotite has diffusion coefficients more than an order of magnitude higher than the zircons in Figure 8. That means the biotite, while not being negligible, did not impede the He outflow as much as the zircon did. That confirmed that the zircon rates were more important.

After that, in the summer and fall of 2002, we tried several times to get lower-temperature zircon data. However, we only discovered

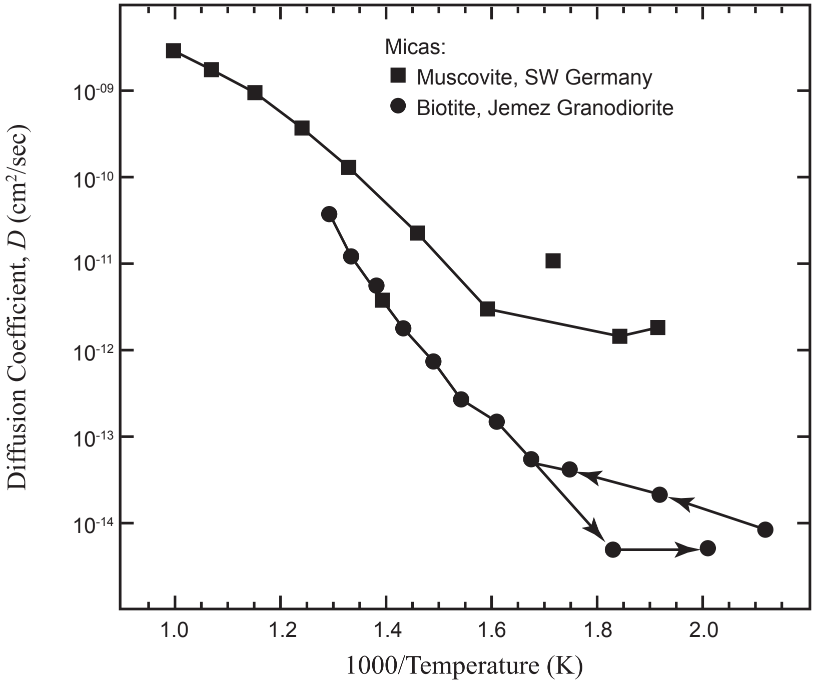

Figure 9. Observed diffusion coefficients in two types of mica. The ordinate is D (not D/a^2).

several wrong ways to make such measurements. First, we asked the experimenter to do new runs on the same batch of zircons, but at lower temperatures. The results were ambiguous, an effect we decided was due to exhaustion of He from the smaller zircons in the batch, thereby increasing the effective radius of the remaining part of the batch [*Fechtig and Kalbitzer*, 1966, section 2.5, p. 72].

Second, we sent the experimenter a new set of zircons from the same depth in GT-2 and asked him to sieve out crystals in the 50–75 μm size range. Before sieving, he decided to leach the crystals in cold concentrated hydrofluoric acid (HF) to remove flecks of biotite clinging to them. Though the technique was new for zircons, it seemed reasonable. However, the values of D/a^2 he then obtained were over fifty times higher than all previous zircon data, both ours and data published by others. Scanning electron microscope images (Figure 10) revealed severe pitting and cracking in the HF-treated zircons. That would allow He to leave the zircons much faster than normally.

These were all the data we had by February 2003, the deadline for the final version of our conference paper [*Humphreys et al.*, 2003a].

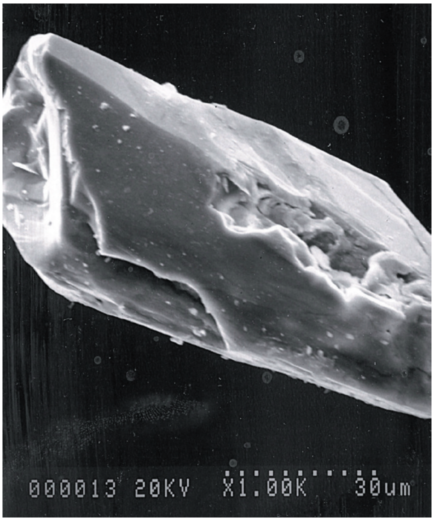

Figure 10. Scanning electron microscope photo of a zircon leached in HF. Compare to an untreated zircon in Figure 11. Note 30-μm scale at lower right. Photo by Mark H. Armitage.

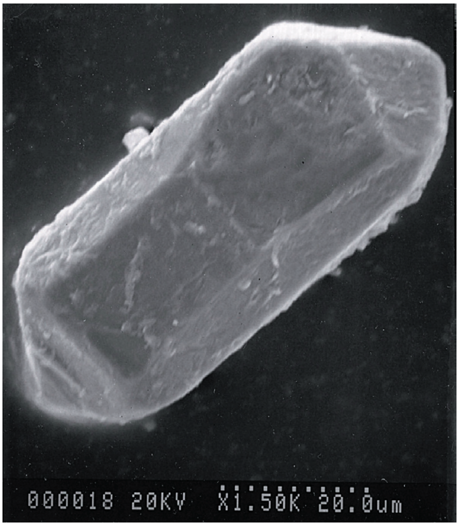

Figure 11. Scanning electron microscope photo of a zircon from size-selected sample 2003. Note 20-μm scale at lower right. Photo by Mark H. Armitage.

6. More Recent Data

In the fall of 2002, we acquired new samples from borehole GT-2, this time from a depth of 1490 m. That is between the depths of Gentry's samples 1 and 2 (see Table 1). We sent them to Activation Laboratories, where they extracted both biotites and zircons. This time they sorted the zircons into several size groups, getting about 1200 crystals in the size range Gentry used, having lengths of 50–75 μm.

Figure 11 shows a scanning electron microscope (SEM) image of one such zircon. Mark Armitage obtained the image in his newly established microscopy laboratory at the Institute for Creation Research, where he also obtained SEM images of the HF-treated zircons the previous section mentioned [*Armitage*, 2004]. In the spring of 2003, we sent our experimenter the 50–75 μm zircons, along with the biotites. This is the sample we labeled "2003" in Table 1 and elsewhere. This time we asked the experimenter (a) not to etch the crystals in HF (unnecessary anyhow because no sieving was needed) and (b) to get zircon diffusivities at lower temperatures. We also asked that he measure more precisely the total He per unit mass in both the zircons and the biotites. In July 2003, one month before the conference, we received his results.

As usual, the experimenter measured the rate of He release at various steps of temperature. Then he put that data into standard formulas to calculate D/a^2, where D is the diffusivity and a is the effective radius of the crystals. The formulas [*Fechtig and Kalbitzer*, 1966, p. 71, equations (5a, b, c), with $R \rightarrow a$] use the fraction (of the total yield) emitted in a given step, the fraction emitted in the previous step, and the duration of the step. The result gives the ratio D/a^2 during that step directly, without the experimenter having to know a specifically. Column 6 of Table 2 shows the resulting values of D/a^2 for the zircons. The experimenter did not report error bounds for D/a^2, but elsewhere he reports:

> In actual practice, we obtain He ages that reproduce to within 6% (2σ), demonstrating some natural variability within grain populations [*Farley*, 2002, p. 833].

The accuracy of such (U-Th)/He ages also reflects the accuracy of the D/a^2 measurement.

The standard formulas assume that the initial distribution of He in the zircons is uniform. But in reality, the zircons would have a "rounded" He-versus-radius profile due to the *in situ* He loss into the biotite. That is, less He would emerge during the initial heating steps than otherwise, because the outer regions of the zircon would be He-depleted. In that case, said the devisers of the standard formulas [*Fechtig and Kalbitzer*, 1966, p. 71],

> The apparent diffusion constants will come out too low, and the activation energies too high.

Also see a similar conclusion by *Reiners et al.,* [2004].

In his report on the 2002 zircon runs (Appendix C), our experimenter advised us that to account for this effect, we should ignore the first set of increasing-temperature steps in his runs. For the 2003 zircons, he reported that we should treat them just the same. Accordingly, we ignored steps 1–9 in calculating D. A more sophisticated analysis could probably extract accurate values of D from the raw He-time data for those steps, but we leave that work for later research.

Diffusion researchers conventionally assume the effective radius a for zircons to be half their length (see next section), which in this case

Table 2. Latest (2003) Jemez zircon diffusion data for about 1200 50–75 μm length zircon crystals from borehole GT-2 at a depth of 1490 m. Column 2 is the temperature at each step, controlled to better than 3°C (Appendix B). Column 3 is the amount of He released ($1\,\text{ncc}=10^{-9}\,\text{cm}^3$ at STP, standard temperature and pressure) at the given temperature step. Column 4 is the time at each step. Column 5 is the cumulative fraction of the total He yield. Column 6 is the value of D/a^2 calculated by the experimenter according to standard formulas, where D is the diffusivity and a is the average effective radius. Column 7 is the value of D assuming $a=30\,\mu\text{m}$, and omitting steps 1–9 according to advice from the experimenter (see text). Total He yield: 1356 ncc at STP (includes fusion step). Total mass = 216 μg. The experimenter did not list results of step 3 because it had "poor temperature control."

Step	Temp (°C)	He (ncc)	Time (sec)	Cumulative Fraction	D/a^2 (sec^{-1})	D (cm^2/sec)
1	50	1.91E-05	3660	1.41E-08	4.73E-21	—
2	100	3.82E-03	3660	2.83E-06	1.91E-16	—
4	200	3.17E-01	3600	0.000256	1.58E-12	—
5	250	1.32E-01	3660	0.000354	1.41E-12	—
6	300	3.43E-01	3660	0.000606	5.78E-12	—
7	350	2.97E+00	3660	0.002798	1.78E-10	—
8	400	9.86E+00	3600	0.010072	2.27E-09	—
9	450	4.28E+01	3660	0.041626	3.89E-08	—
10	500	1.48E+02	3600	0.150546	5.55E-07	4.99E-12
11	475	3.93E+01	3660	0.179567	2.63E-07	2.37E-12
12	425	4.90E+00	3600	0.183185	3.72E-08	3.35E-13
13	375	6.29E-01	3660	0.183649	4.75E-09	4.28E-14
14	325	7.77E-02	3600	0.183706	5.98E-10	5.38E-15
15	275	1.01E-02	3660	0.183714	7.64E-11	6.88E-16
16	225	3.56E-03	7260	0.183716	1.36E-11	1.22E-16
17	175	7.78E-04	7260	0.183717	2.97E-12	2.68E-17
18	205	2.03E-03	7200	0.183718	7.81E-12	7.03E-17
19	255	4.25E-03	3660	0.183722	3.22E-11	2.90E-16
20	305	3.03E-02	3600	0.183744	2.33E-10	2.10E-15
21	355	2.41E-01	3660	0.183922	1.83E-09	1.65E-14
22	405	1.94E+00	3600	0.185352	1.50E-08	1.35E-13
23	455	1.47E+01	3600	0.196188	1.18E-07	1.06E-12
24	505	8.09E+01	3660	0.255886	7.87E-07	7.09E-12
25	460	1.35E+01	3660	0.265832	1.57E-07	1.41E-12
26	410	1.86E+00	3660	0.267207	2.23E-08	2.00E-13
27	360	2.46E-01	3600	0.267389	3.00E-09	2.70E-14
28	310	3.18E-02	3660	0.267412	3.82E-10	3.43E-15

gives us an average value for *a* of about 30 µm. Multiplying column 6 by the resulting value of a^2 gives us values of the diffusivity *D* for points 10–28, which we show in column 7 of Table 2. I estimate that the 1σ error in *D* is less than ±30% (see Endnote iii).

7. A New Creation Model

We need a theoretical framework in which we can interpret the diffusion data of the previous section. As we mentioned at the end of section 4, in our first Creation model we wrongly assumed that the zircons were a negligible impediment to the He diffusion. In this section we construct a new Creation model.

As before, the Creation model starts with a brief burst of accelerated nuclear decay generating a high concentration C_0 of He uniformly throughout the zircon (like the distribution of U and Th atoms), but not in the surrounding biotite. After that the He diffuses out of the zircon into the biotite for a time *t*. As in our previous model, we chose $t = 6000$ years. The time is short enough that the additional amount of He generated by normal nuclear decay would be small compared to the initial amount. We assume the temperatures to have been constant at today's values. We will show in Section 8 that this assumption is generous to uniformitarians.

Because the biotite diffusion coefficients are not too different from the zircon coefficients, we should have a model accounting for two materials. Diffusion in zircon is, as far as anyone knows, approximately isotropic, with He flowing essentially at the same rate in all three directions. Diffusion in biotite is not isotropic, because most of the He flows two-dimensionally along the cleavage planes of the mica. But accounting for anisotropy in the biotite would be quite difficult, so we leave that refinement to the next generation of analysts. (See Appendix D, Section D4 for estimate of size of the error involved in assuming isotropy in biotite.) To keep the mathematics tractable, we will assume spherical symmetry, with a sphere of zircon of effective radius *a* inside a spherical shell of material having an outer radius *b*, as Figure 12 shows. Then the concentration *C* will depend only on time and the distance *r* from the center.

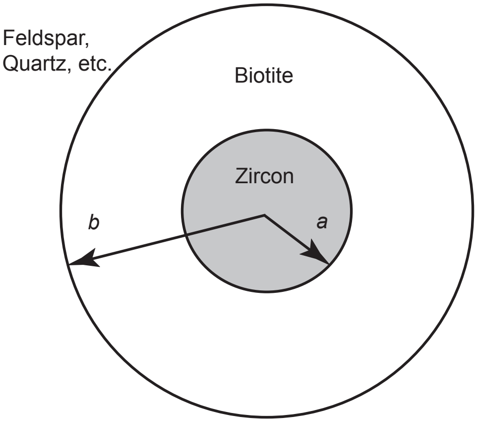

Figure 12. Spherical approximation of the zircon-biotite system.

Let us consider the values we should assign to *a* and *b*. Magomedov's zircons were between 100 and 200 µm long [*Magomedov*, 1970, p. 263], for an average length of about 150 µm. He assigned the crystals an effective radius of half the average length, or 75 µm. Gentry selected zircons between about 50 µm and 75 µm, for an average that we will round off to 60 µm. Half of that gives us an effective radius for our analysis of the Jemez zircons with a 1σ estimate of error (see Endnote iii):

$$a = 30(\pm 1.5)\ \mu\text{m} \tag{6}$$

This is an average value, representing all the crystals in the size-selected sample. Note that this value is larger than the 22 µm I chose in our first Creation model [*Humphreys*, 2000, p. 347]. See Appendix D, Section D4. Biotite in the Jemez granodiorite is in the form of flakes averaging about 0.2 mm in thickness and about 2 mm in diameter. Because the cleavage planes are in the long direction, and diffusion is mainly along the planes, the diameter is the relevant dimension for diffusion. That gives us a nominal outer radius for the biotite flake of:

$$b \approx 1000\ \mu\text{m} \tag{7}$$

Because *b* is more than thirty-two times larger than *a*, the disk-like (not spherical) volume of biotite the He enters is more than 1000 ($\sim 32^2$) times the volume of the zircon. This consideration affects the boundary conditions we choose for $r=b$, and how we might interpret sample 6 (see Section 2), as follows. To predict D in zircon with the equations below, we only need to know the value of b to within an order of magnitude, because it tends to cancel itself out in an analysis of errors. The physical reason for the cancellation is that for large values of b/a, He concentration in the biotite generally remains much lower than the He concentration in the zircon, so that the former would not significantly affect the flow of He from the zircon. That applies to samples 1–5.

However, let us consider sample 6. Suppose that He could not escape the biotite at all. Then as diffusion proceeds, C would decrease in the zircon and increase in the biotite, until the concentration was the same throughout the two materials. After that C would remain essentially constant, at about 0.001 C_0. The fraction Q/Q_0 remaining in the zircon would be about 0.001, which is just what Gentry observed in sample 6.

So a possible explanation for sample 6 is that diffusion into the surrounding materials (feldspar, quartz), and leakage (along grain boundaries) was slow enough (during the relatively short time t) to make the outflow of He from the biotite negligible. For that sample, the temperature and diffusivity were high enough for He to spread uniformly through both zircon and biotite during that time.

Our measurements on sample 2002 (see Appendix B) showed that the He concentration in the Jemez biotite at a depth of 750 m was small, only about $0.32 \times 10^{-9}\,\mathrm{cm}^3$ STP (standard temperature and pressure) per microgram (μg). Taking into account the difference in density of biotite and zircon ($3.2\,\mathrm{g/cm}^3$ and $4.7\,\mathrm{g/cm}^3$), that corresponds to almost exactly the same amount of He per unit volume as sample 6 contained. Our measurements on sample 2003 (see Section 10) confirm that. This suggests the zircon and biotite were near equilibrium in sample 6, thus supporting our hypothesis.

At lower temperatures, for He retentions greater than 0.001, C in the biotite would be lower than C in the zircon. In that case the boundary at $r=b$ would not significantly affect the outflow of He from the zircon. We will assume this was approximately true for sample 5 also, but not for sample 6. To simplify our analysis for samples 1 through 5, we will assume the usual boundary condition, that the concentration $C(r)$ falls to zero at radius $r = b$:

$$C(b) = 0 \tag{8}$$

Choosing a different boundary condition would have little effect on the result, because it turns out that in the short time available, little He could leave the biotite under any circumstances. For the initial conditions, we assume that the concentration is a constant, C_0, inside the zircon, and zero outside it:

$$\text{At } t = 0: \quad C(r) = C_0 \text{ for } r < a, \quad \text{and} \quad C(r) = 0 \text{ for } r > a \tag{9a, b}$$

After time zero, there also must be continuity of both C and He flow at $r = a$. We need a solution to the diffusion equation, equation (1), in its radial form, for the above boundary conditions. In 1945, Bell published such a solution for the corresponding problem in heat flow [*Bell*, 1945, p. 46, equation (4B)]. His solution, which is mathematically complex, allows for different diffusion coefficients in the two regions. We will simplify the solution considerably by making the diffusion coefficients the same in both regions. Because the diffusion coefficient of biotite is somewhat higher than that of zircon at the temperatures of interest, our solution will have slightly slower (no more than 30% slower) He outflows and correspondingly longer times than the real situation. This approximation is generous to the uniformitarian point of view because it increases the time He could remain in the zircons. For more discussion of the above boundary conditions, and possible alternatives to them, see Appendix D, Section D4.

With the above simplification, Bell's equation reduces to one given by Carslaw and Jaeger [*Carslaw and Jaeger*, 1959, p. 236, equation (19)]. After making the simple changes required to go from heat flow to atomic diffusion [*Crank*, 1975, p. 8, equation (1.21)], and accounting for notation differences (note meanings of *a* and *b*), we get the following solution:

$$C(r,t) = \frac{2C_0}{r}\sum_{n=1}^{\infty}\frac{1}{n\pi}\left(\frac{b}{n\pi}\sin\frac{n\pi a}{b} - a\cos\frac{n\pi a}{b}\right) \times \sin\frac{n\pi r}{b}\exp\left(-n^2\frac{\pi^2 Dt}{b}\right) \tag{10}$$

where *D* is the diffusion coefficient of zircon. Next we need to determine the fraction Q/Q_0 of He retained in the zircon after diffusion takes place for time *t*. First, note that $Q(t)$ and Q_0 are the volume integrals of $C(r, t)$ and C_0 in the zircon:

$$Q(t) = 4\pi\int_0^a C(r,t)r^2 dr, \quad Q_0 = \frac{4}{3}\pi a^3 C_0 \tag{11a, b}$$

Volume integrating equation (10) as required by equation (11a) and dividing by equation (11b) gives the fraction of He retained in the zircon after time *t* elapses:

$$\frac{Q(t)}{Q_0} = \sum_{n=1}^{\infty} S_n \exp\left(-n^2\frac{\pi^2 Dt}{b^2}\right) \tag{12}$$

where we define the function S_n as follows:

$$S_n = \frac{6b^3}{n^4\pi^4 a^3}\left(\sin\frac{n\pi a}{b} - \frac{n\pi a}{b}\cos\frac{n\pi a}{b}\right)^2 \tag{13}$$

To solve equation (12), let us rewrite it in terms of a new variable, *x*, and a new function, $F(x)$, as follows:

$$F(x) = \frac{Q}{Q_0}, \qquad \text{where } F(x) = \sum_{n=1}^{N} S_n \exp(-n^2 x), \qquad \text{and } x = \frac{\pi^2 Dt}{b^2} \tag{14a, b, c}$$

Now we can use software like *Mathematica* [*Wolfram*, 1991] to find the roots of equation (14a), that is, to find the values of *x* for which $F(x)$ will give us particular values of the retention fraction Q/Q_0. When the latter and b/a are large, the series in equation (14b) does not converge rapidly. For our value of b/a, 33.3, it was necessary to go out to $N = 300$ to get good accuracy. Table 3 lists the resulting values of *x*, and the values of D necessary to get those values from equation (14c) using a time of 6000 years, $t = 1.892 \times 10^{11}$ seconds. The estimated errors in D essentially result from the reported ±30% errors (which we conservatively assumed to be 1σ random errors) in Q/Q_0. The other errors, such as in the average values of a (less than ±5%) and b (negligible effect), are much smaller. When we take the square root of the sum of the squares of the various errors, the effect of the ±30% error completely dominates.

Table 3. New Creation model.

Sample	T (°C)	Q/Q_0	x	D (cm²/sec)	1σ Error (%)	
1	105	0.58±0.17	5.9973×10^{-4}	3.2103×10^{-18}	+122	-67
2	151	0.27±0.08	2.4612×10^{-3}	1.3175×10^{-17}	+49	-30
3	197	0.17±0.05	4.0982×10^{-3}	2.1937×10^{-17}	+39	-24
4	239	0.012±0.004	3.3250×10^{-2}	1.7798×10^{-16}	+33	-18
5	277	~0.001	1.8190×10^{-1}	9.7368×10^{-16}	—	—

In summary, the fifth column shows the zircon diffusion coefficients that would be necessary for the Jemez zircons to retain the observed fractions of He (third column) for 6000 years at the temperatures listed in the second column. Column 6 gives the (probably overestimated) 1σ error in the predicted values of D.

This new model turns out to be very close to my previous Creation model—within 0.5% for sample 1 and 0.05% for the others—despite the different assumptions and equations. The effect of two changes (going from cavity in biotite to solid in biotite, and increasing the effective radius from 22 μm to 30 μm) almost completely canceled each other out (see Appendix D, Section D4.) Thus my previously published predictions [*Humphreys*, 2000, p. 348, Figure 7] of diffusion coefficients still happen to be numerically valid—no thanks to me! But the numbers should be re-interpreted to apply to zircon, not biotite.

We will compare the data not only to this new model, but also to a uniformitarian model, which we describe in the next section.

8. Uniformitarian Model

In the RATE book [*Humphreys*, 2000, p. 346], we outlined a simple model appropriate for the uniformitarian view, with its billions of years, of the history of the rock unit:

> … steady low-rate radioactive decay, He production, and He diffusion for 1.5 billion years at today's temperatures in the formation.

Our assumption of constant temperatures is generous to the uniformitarian model. Two geoscientists from Los Alamos National Laboratory constructed a theoretical model of the thermal history of the particular borehole (GT-2) we are concerned with [*Kolstad and McGetchin*, 1978, p. 213, Figure 11]. They started by assuming "a background vertical geothermal gradient of 25°C/km." That means initial conditions with absolute (K) temperatures 16 to 31% lower than today for samples 1 through 6, putting them in the low-slope "defect" range of diffusion. Their model then has an episode of Pliocene-Pleistocene volcanism starting to increase the temperature several megayears ago. It would peak about 0.6 Ma ago at temperatures roughly 50 to 120ºC above today's values, depending on depth. After the peak, temperatures would decline steadily until 0.1 Ma ago, and then level off at today's values.

Later studies [*Harrison et al.*, 1986; *Sasada*, 1989] add a more recent pulse of heat and have past temperatures being higher, 110 to 190ºC more than today's levels just 24,000 years ago, and higher before that [*Harrison et al.*, 1986, p. 1906, Figure 9]. This would put the samples well into the high-slope "intrinsic" range of diffusion.

The effect of such heat pulses would be great. For several million years, the diffusion coefficients would have been about two to three orders of magnitude higher than today's values. During the previous 1.5 billion years, supposedly at lower temperatures than today, the diffusion rates would have been on the "defect" line (Figure 5) and therefore not much below today's levels. Thus the long time at lower temperatures would not compensate for high losses during the few million years at higher temperatures. This makes our assumption of constant temperatures at today's values quite favorable to the uniformitarian scenario. For further comments, see Section 10 and Figure 16.

As we will see, the long uniformitarian timescale requires zircon diffusion coefficients to be about a million times slower than the measured biotite coefficients. That means the biotite would not be a significant hindrance to the He flow in the uniformitarian model, and the results would not be much different than those for a bare zircon. For further comments on that assumption, see Appendix D, Section D4, change (3). With continuous production of He, the concentration C in the zircon would reach its steady-state level relatively quickly (see Section 11) and remain at that level for most of the alleged 1.5 billion years. Again we assume a spherical zircon of radius a. Carslaw and Jaeger give the corresponding solution for heat flow [*Carslaw and Jaeger*, 1959, p. 232, case VIII)]. Converting to the notation for atomic diffusion shows us how the steady-state concentration C in the zircon depends on the radius r from the center:

$$C(r) = \frac{Q_0}{\tfrac{4}{3}\pi a^3} \frac{\left(a^2 - r^2\right)}{6Dt}, \text{for } r \leq a \tag{15}$$

Here Q_0 is the total amount of He that would be produced in time t. That is, Q_0/t is the He production rate. As before, D is the diffusion coefficient of zircon, and a is the effective radius. Using equation (11a) to integrate equation (15) and dividing by Q_0 gives us the fraction of He Q/Q_0 in the zircon in the steady-state condition:

$$\frac{Q}{Q_0} = \frac{a^2}{15Dt} \tag{16}$$

Table 4 gives us the zircon diffusion coefficients required to give the observed retentions for $a = 30\,\mu\text{m}$ and $t = 1.50$ (± 0.02) billion years $= 4.7 \times 10^{16}$ sec ($\pm 1.3\%$).

The same reasoning on sample 6 applies for this model as for the Creation model, except that it is less likely the He could remain totally sealed in the biotite for over a billion years. For the other samples, this model is exactly the same as our previously published "evolution" model [*Humphreys*, 2000, p. 348, Figure 7].

Table 4. Uniformitarian model.

Sample	*T* (ºC)	Q/Q_0	*D* (cm^2/sec)	1σ Error (%)
1	105	0.58±0.17	2.1871×10^{-23}	±30
2	151	0.27±0.08	4.6981×10^{-23}	±30
3	197	0.17±0.05	7.4618×10^{-23}	±30
4	239	0.012±0.004	1.0571×10^{-21}	±30
5	277	~0.001	1.2685×10^{-20}	—

9. Comparing Data and Models

Figure 13 shows the new Jemez zircon data of Table 2, plotted with the two models for comparison. The data (blue dots) fall right upon the predicted Creation model (green squares)—as close as errors in the data and approximations in the model would lead us to expect (notice the ±2σ error bars on both models and data in the figure). The data points extend past the "knee" of the model at 197ºC (abscissa = 2.13), into the lower-temperature "defect" region determined by radiation damage in the crystals. This was quite important to examine, because the defect part of the curve can vary greatly from site to site (see Sections 3 and 4). Even in the defect region, the data agree quite well with the model. It is not often in science that experimental data so clearly validate a pre-published numerical model.

The data also resoundingly reject the uniformitarian model (red squares). The points of that model are the values of diffusivity required to retain the observed amounts of He for 1.5 billion years at *today's* temperatures in the rock unit. However, as I mentioned in the previous section, uniformitarian thermal models of the rock unit require that the temperatures have been *higher* in the past [*Kolstad and McGetchin*, 1978; *Harrison et al.*, 1986; *Sasada*, 1989]. So the points of our uniformitarian model are below the average temperatures during the alleged eons. A more accurate depiction would slide the uniformitarian model points horizontally leftward to represent the allegedly higher average temperatures. That would make the vertical gap between that model and the data even larger, as the left-hand side of Figure 16 (in

Section 10) shows. Thus the uniformitarian model in Figure 13 is very generous to uniformitarians, minimizing the gap. Even so, the data points are about 100,000 times higher than the model points. At their closest, the lower 2σ bound of the data and the upper 2σ bound of the uniformitarian model are more than twenty-five standard deviations apart. Uniformitarianism has totally failed this experimental test.

We can also compare the new diffusivities with the observed retentions to calculate the age of the zircons. Turning equation (14c) around gives us

$$t = \frac{b^2 x}{\pi^2 D} \tag{17}$$

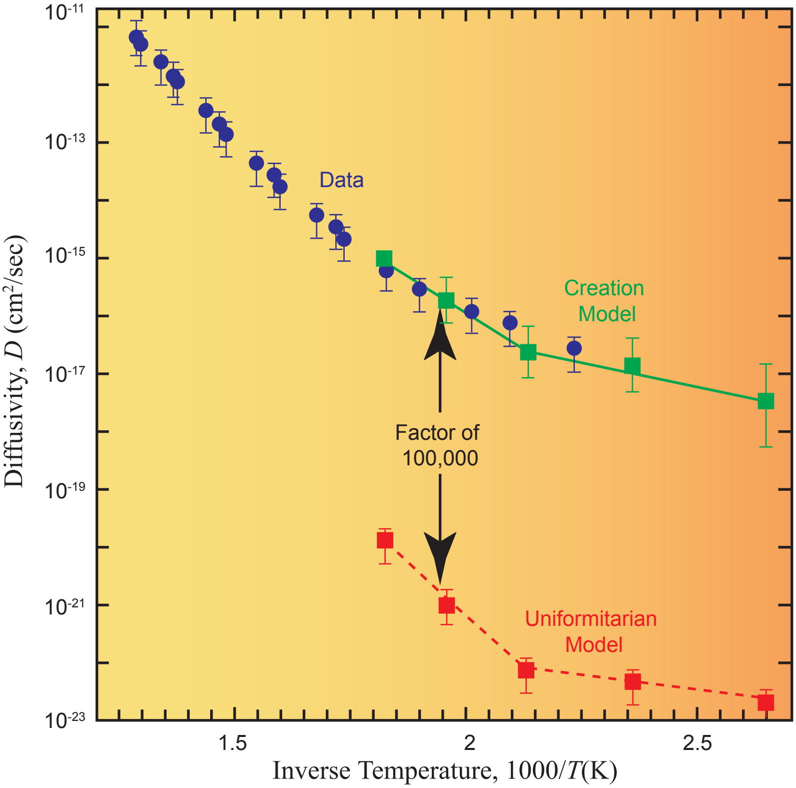

Figure 13. The 2003 zircon data line up very well with the Creation model, and they resoundingly reject the uniformitarian model. The ordinate is D (not D/a^2). Error bars show ± 2σ bounds on data and models.

Using *a/b* = 0.03, the values of D/a^2 from Table 2, and the values of *x* from Table 3 gives us the length of time diffusion would have been occurring. Table 5 shows the results of doing that.

Diffusivities in this table come from best exponential fits to nearby measured points from Table 2, column 7. Because our lowest measured value for *D* is at 175°C, we extrapolated 24°C down to the temperature of sample 2 but not further down to those of samples 2003, 1, or 2002. Then we calculated ages (see Endnote iv) as we did in our paper for the Fifth International Conference on Creationism [*Humphreys et al*., 2003a, Sections 6 and 8], putting the *x*-values of Table 3 and the values of *D* below into equation (17) to get the values for the age *t* we show above. See our comments in Section 10 (related to Figure 15) about sample 3, which in Table 5 has the greatest deviation from the average age. The average was 5681 years with a sigma (square root of variance) of 1999 years. We round off those numbers to 6000±2000 years. Our value of σ here agrees with the 1σ bounds we get from an error analysis using Table 3 (see Endnote v).

Summarizing Table 5 and considering the 1σ estimates of error, the He diffusion age of these zircons is between *4000 and 8000 years*. This is far short of the 1.5 billion year uniformitarian age. The data offer no hope for the uniformitarian model, differing from it by more than 25 standard deviations. That large a separation signifies rejection of the

Table 5. Helium diffusion age of zircons.

Sample	Temperature (°C)	Retention (%)	Diffusivity (cm²/sec)	Age (years)
2002	96	~80	—	—
1	105	58	—	—
2003	125	42	—	—
2	151	27	1.09×10^{-17}	7270
3	197	17	5.49×10^{-17}	2400
4	239	1.2	1.87×10^{-16}	5730
5	277	~0.1	7.97×10^{-16}	~7330
			Average:	5681
			Sigma:	1999

Table 6. Billion-year uniformitarian retentions versus observed retentions.

Sample	T	Measured D/a^2	Helium Retentions Q/Q_0	
	(°C)	(sec^{-1})	After 1.5 billion years	Observed
2002	96	—	—	~0.800
1	105	—	—	0.580
2003	124	—	—	0.420
2	151	1.21×10^{-12}	1.16×10^{-6}	0.270
3	197	6.10×10^{-12}	2.31×10^{-7}	0.170
4	239	2.08×10^{-11}	6.77×10^{-8}	0.012
5	277	8.86×10^{-10}	1.59×10^{-8}	~0.001

uniformitarian hypothesis with an extremely high level of confidence (see endnote vi). The zircon data show a knee, where the data break off horizontally to the right into a shallow-slope "defect" line. But even if that had not been the case, the high-slope "intrinsic" line would still pass well above the uniformitarian model.

We can also use these observed data to estimate what He retentions Gentry should have found if the zircons were really 1.5 billion years old. If no He could leak out of the biotite during that time, then all of the samples would have had retentions of about 0.001, much less than all samples but number 5 [see Section 7 between equations (7) and (8)]. However, we know that He can diffuse through the surrounding materials, quartz and feldspar (so even sample 5 would retain much less than 0.001). By assuming those materials are comparatively negligible hindrances, we can put the diffusivity data of Table 5 into equation (16) to get the "unrestricted outflow" retentions after 1.5 billion years. Table 6 shows the results.

So the best uniformitarian estimate of retentions for all samples would be somewhere between 0.001 (zero flow into surrounding minerals) and the small numbers in column 4 (unrestricted flow into surrounding minerals). That is not what we observe. In summary, the observed diffusion rates are so high that if the zircons had existed for 1.5 billion years at the observed temperatures, all samples would have retained *much less He than we observe*. That strongly implies they have not existed nearly so long a time. In Appendix D we consider mechanisms that might limit He diffusion and increase He retention. We find no mechanism that is capable of retaining large amounts of He for even a few million years, much less billions of years.

10. Closing Some Loopholes

After stepwise heating the 216 µg of zircons in sample 2003 to get the diffusivity data, our experimenter raised the temperature to a high value and held it there long enough to get the rest of the He out of the crystals. The total yield of He from the zircons was 1356 ncc (1 ncc = 10^{-9} cm^3 STP = 0.4462 × 10^{-4} nanomole), or 6.05 × 10^{-2} nmol (1σ error ±3%). Dividing by the mass (±1%) gives us 6.28 ncc/µg, or 303 nmol/g (±3%). Multiplying the latter value by the density of zircon, 4.7 g/cm^3 (±2%), gives us the He concentration in the zircon: 1320 nmol/cm^3 (± 4%).

For the 5.562 mg (±1%) of biotite, the total yield of He was 257 ncc (±3%), giving 2.06 nmol/g (±3%). Multiplying by the density of biotite, 3.2 g/cm^3 (±2%) gives us the He concentration in the biotite: 6.57 nmol/cm^3 (±4%).

These data are quite useful in closing possible loopholes in our case. First, the 6.28 ncc/µg yield of these zircons is quite consistent with Gentry's retention data. Gentry's (±30%) estimate of radiogenic He deposited in the zircons, 15 ncc/µg ±30% (1σ), is consistent with our data on radiogenic Pb in the zircons. Dividing our retention by that value gives us a retention fraction of 0.42±0.13. Almost all of that error is systematic, caused by Gentry's ±30% error. That is, if we were to correct all retentions, both Gentry's and ours, with a new estimate of He deposited, our point would move up or down together with Gentry's points. Here we only want to compare our retention with those of Gentry, so I will leave the systematic error out of the comparison. The He measurement error, on the other hand, has a 1σ random error of ±3% (see Endnote iii). These zircons came from a depth of 1490 m, nearly midway between Gentry's samples 1 and 2 in Table 1. The interpolated temperature at that depth would be 124 (±1)°C. Figure 14 shows that our new retention point fits quite well between Gentry's retentions for samples 1 and 2. This supports the validity of Gentry's

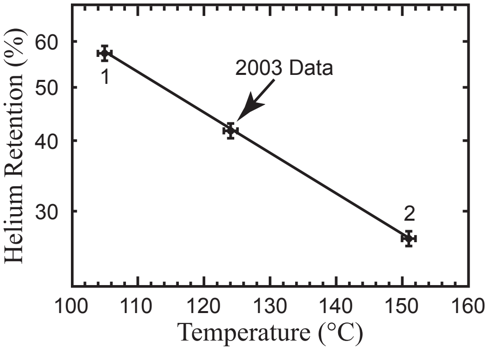

Figure 14. New retention point confirms Gentry's retention data. Error bars show 1σ measurement uncertainties.

retention measurements.

Second, the concentration of He in the zircon, 1320 nmol/cm^3, is about 200 times greater than the concentration in the surrounding biotite, 6.6 nmol/cm^3. Because the laws of diffusion require flow from greater to lesser concentrations, these data mean that He is moving *out* of the zircons *into* the biotite, not the other way around.

Third, because the average volume of the biotite flakes is hundreds of times greater than that of the zircons (Section 7), the amount of He in the biotites is on the same order of magnitude as the amount of He lost by the zircons. That rebuts a uniformitarian conjecture [*Ross*, 2003] that there might have been vast amounts (100,000 times greater than the already-large observed amounts) of non-radiogenic primordial He in the zircons 1.5 billion years ago.

Our new He retention fraction (0.42 at 124°C) can be treated the same way as we treated Gentry's retention data to make a prediction of diffusion rates. That is, we can use our retention figure to calculate what value of *D* at 124°C would be required if the zircons were 6000 years old. Figure 15 shows how this "retrodiction" point fits very well with the diffusion rate data and the Creation model prediction.

In Figure 15, I have relabeled the abscissa by temperature and have redrawn the lines in accord with the new data. The largest outlier from the lines is the model point at 197°C. The difference suggests the true retention fraction for that sample might have been about half the

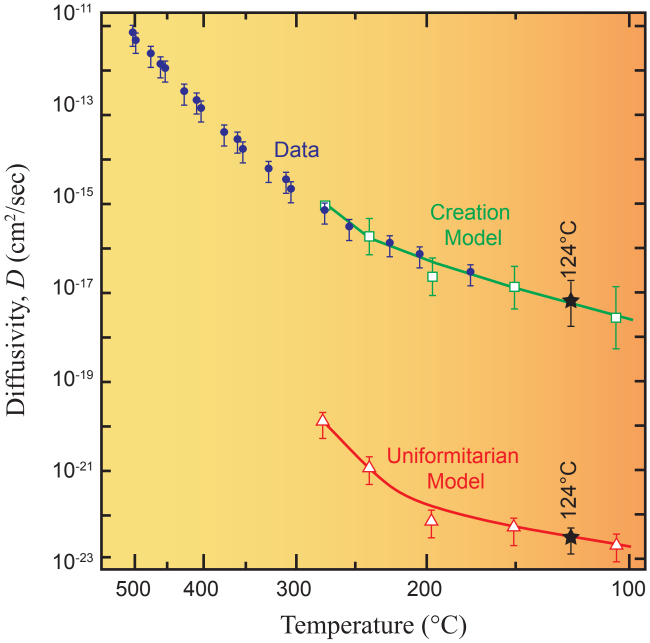

Figure 15. Lines of Figure 13 redrawn in accordance with the 2003 data. Stars with "124°C" above are the diffusivities required by our new retention datum (0.42) and the ages assumed by the two models. Bars show the 2σ error bounds on data and models. Error for leftmost (277°C) Creation model point is undetermined (Section 2).

fraction *Gentry et al.* [1982] reported (Table 1, sample 3). Whatever the cause, a two-fold discrepancy for one point pales into insignificance in light of the enormous 100,000-fold discrepancy between the observed diffusivities and all points of the uniformitarian model.

Some people might wonder if temperatures in the Jemez granodiorite before 6000 years ago were low enough for long enough to make the diffusion coefficients small enough to retain the He. We discussed that possibility in Section 8, but here we point out how low such temperatures are likely to be.

In Figure 15, the right-hand four points, the 175°C experimental point (solid dot) and the three points deduced from retentions and a 6000 year age (hollow squares and star) appear to make a fairly straight line. That suggests that below 175°C, the "defect" slope has established itself. In that case, the best linear fit (to $\ln D$ vs $1/T$) gives parameters (with 1σ error bounds) of the defect line for these zircons from borehole GT-2:

$$E_1 = 10.19^{+0.59}_{-0.62} \text{ kcal/mol}, \quad D_1 = (2.49 \pm 1.69) \times 10^{-12} \text{ cm}^2\text{/sec} \qquad (18)$$

Because E_1 is small, the slope of the defect line is small. Figure 16 extrapolates this line and its 1σ error bounds down to very low temperatures. The intercept with $D = 10^{-23}$ cm²/sec is (note minus sign):

$$T = -78^{+21}_{-14}\,^{\circ}\text{C}$$

By coincidence, that happens to be the temperature of sublimating *dry ice* (frozen CO_2). The "Cold" uniformitarian model in Figure 16 simply slides the "Present Temperatures" uniformitarian model of Section 8 rightward far enough to meet the dotted line, the diffusivities extrapolated from our data. The amount of shift required means that to get the diffusion coefficients low enough, say on the order of 10^{-23} cm²/sec, to allow a billion-year time-scale, the temperature in the granodiorite would have to have been extremely low, about that of dry ice. (In our previous publications, we slid the "Cold" model to even lower temperatures, but the data and fit here are more accurate.) No geoscientist we know would advocate an earth that was *cryogenic* for 1.5 billion years!

Moreover, as we commented in Section 8, uniformitarian models of the thermal history of the rock unit call for much *higher* past temperatures than the ones at present, not lower temperatures. The "Hot" model in Figure 16 slides the "Present Temperatures" model to the left far enough to roughly account for the uniformitarian Pliocene-Pleistocene thermal models. Notice that in that case the discrepancy between data and model increases to a factor of about *100 million*. The alleged hot episode of several million years would have completely wiped out any He that might have accumulated during the alleged previous 1.5 billion years. That is why our assumption of constant temperatures at today's levels is very generous to the uniformitarian model.

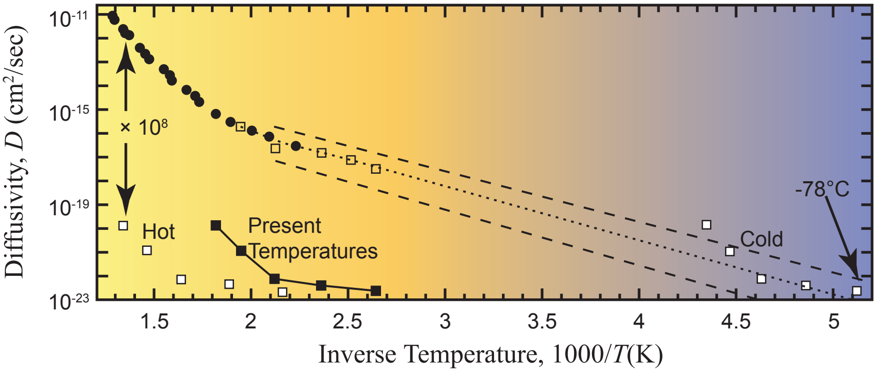

Figure 16. Different temperatures cannot rescue the uniformitarian model. Errors for data and models are the same as in Figure 15. Dotted line is best fit to last four points. Dashed lines are 1σ upper and lower bounds to fit.

11. "Closure Temperature" does not Help the Uniformitarian Model

Some people misunderstand the geoscience concept of *closure temperature*, thinking that zircons cooling below that temperature are permanently closed systems and thereafter would lose no significant amounts of He by diffusion. That argument would not affect our samples 2–5 because they are *above* the closure temperature our experimenter calculated, 128°C (Appendix C). However, our samples below the closure temperature would also not be affected, because it turns out that even well below the closure temperature, zircons can *re-open* and lose large amounts of He. Here we explain closure temperature and re-opening, and show that in the uniformitarian scenario, even the cooler Jemez granodiorite zircons would re-open early in their history.

Consider a hot zircon cooling down in newly formed granite. If the cooling rate is constant, then the seminal article by Martin Dodson [*Dodson*, 1973] on closure temperature shows that the diffusion coefficient D (of He moving out of the zircon) decreases exponentially with a time constant τ given by:

$$\tau = \frac{RT^2}{E_0\left(\dfrac{dT}{dt}\right)} \tag{19}$$

where T is the absolute temperature, dT/dt is the cooling rate, R is the gas constant, and E_0 is the activation energy in the "intrinsic" region (Section 3).

In the uniformitarian scenario, nuclear decay produces He at a nearly constant rate. At the beginning, when the zircon is very hot, He diffuses out of the crystal as fast as nuclear decay produces it. But as the zircon cools, it will eventually reach a temperature below which the *loss rate becomes less than the production rate.* That point is essentially what Dodson meant by the "closure" temperature. He showed that for a constant cooling rate the closure temperature T_c is

$$T_c = \frac{E_0}{R \ln\left(A\, \tau \dfrac{D_0}{a^2} \right)} \tag{20}$$

where A is a dimensionless constant (55 for a sphere), D_0 is the "intrinsic" intercept in Figure 5, a is the effective radius of the crystal, and τ is the diffusion time constant given by equation (19). Since τ depends on the cooling rate, hence affecting T_c somewhat, geoscientists imply some conventional cooling rate when they specify a closure temperature. In Appendix C our experimenter assumes a cooling rate of 10°C per million years and finds that the closure temperature of the Jemez granodiorite zircons is 128ºC.

After the zircon cools below the closure temperature, He begins to accumulate in it, as Figure 17 shows. Later, as the temperature levels off to that of the surrounding rock, the diffusion coefficient D becomes constant. (The case of changing long-term temperatures is harder to analyze, but there will still be a time of re-opening.) As the amount of He in the zircon increases, Fick's laws of diffusion (Section 3) says the loss rate also increases. Eventually, even well below the closure temperature, the *loss rate approaches the production rate*, an event we call the "re-opening" of the zircon. Then the amount of He in the zircon will level off at a steady-state value, which we called Q in equation (16). After that, the zircon will again lose He as fast as nuclear decay produces it.

Let us estimate the *closure interval*, the length of time t_{ci} the zircon

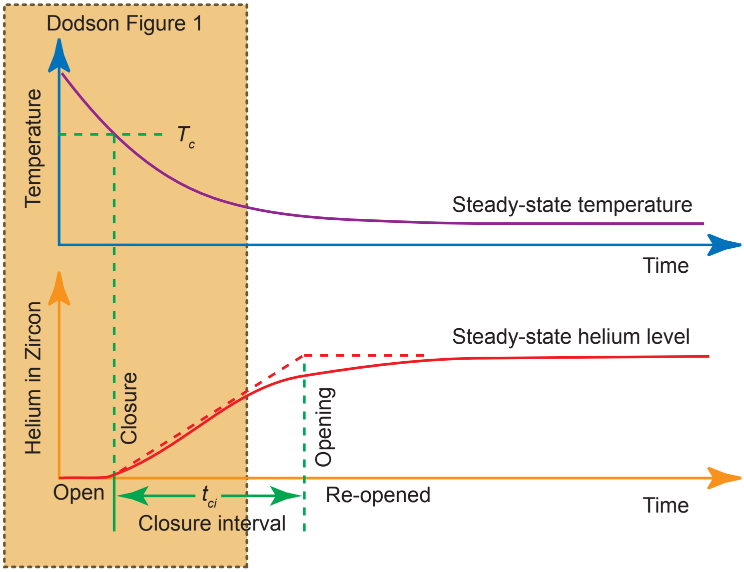

Figure 17. Closure and re-opening of a zircon. Dotted-line box on the left contains the essentials of Dodson's Figure 1, which did not extend far enough in time to show re-opening.

remains closed before re-opening. As we remarked just below equation (15), the He production rate is Q_0 / t, where t is the uniformitarian age of the zircon, 1.5 billion years. Assuming a linear rise as a first approximation, the production rate multiplied by t_{ci} is roughly equal to the steady-state value of Q, which is the right-hand side of our equation (16) multiplied by Q_0

$$\left(\frac{Q_0}{t}\right) t_{ci} \approx \left(\frac{a^2}{15Dt}\right) Q_0 \tag{21}$$

Solving for t_{ci} gives us the approximate closure interval:

$$t_{ci} \approx \frac{a^2}{15D} \tag{22}$$

If the closure interval were long compared to the age of the zircon, then the zircon would indeed be a closed system. But would that be the case in the uniformitarian view of the Jemez zircons? Using the effective radius of the zircons, 30 μm, and the measured values of D (Figure 15) in equation (22), gives us t_{ci} values between *a few dozen years and a few thousand years*, depending on the temperature of the sample in the borehole. Those times are very small compared to the uniformitarian age of 1.5 billion years.

So even if the zircons had cooled rapidly and reached closure temperature early in their history, our measured diffusion rates say they would have re-opened shortly after that. During most of the alleged eons the zircons would have been an open system. They would be losing as much He as the nuclear decay produced. Thus, in this case, closure *temperature* does not help the uniformitarian model, because the closure *interval* is brief.

12. Discussion: A Tale of Two Hourglasses

Experiments have strongly vindicated what creationists felt when Gentry reported the high He retentions over twenty years ago. The He indeed could not have remained in the zircons for even a million years, much less the alleged 1.5 billion years. Even more exciting, our more recent experiments give a He diffusion age of 6000 years (with a 1σ error of ±2000 years), which resonates strongly with the date of Creation we get from a straightforward Biblical chronology.

Figure 18 illustrates the contrast between this He age and the radioisotopic age. It shows two different "hourglasses," representing He diffusion and U-Pb nuclear decay. These hourglasses give drastically different dates.

We have much data to show that we have read the He hourglass correctly:

- U-Pb data give us the initial amount of sand (He) in the top half (the zircon).
- Gentry's measurements, confirmed by ours, give us the present amount of sand in the top half.
- Our diffusion rate experiments show how fast sand is presently trickling (diffusing) out of the top half into the bottom half (the biotite).

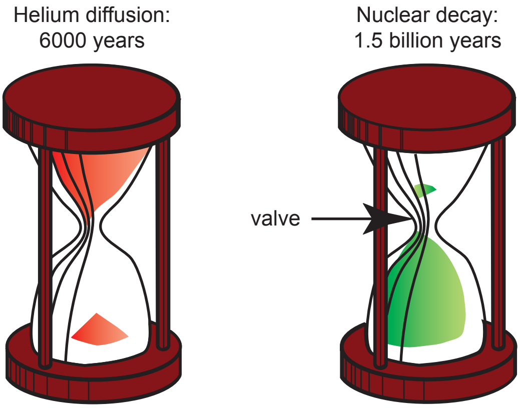

Figure 18. Two hourglasses representing two methods of dating zircons. "Valve" represents nuclear decay acceleration.

- Our measurements show roughly the right amount of sand in the bottom half (He in the biotite).

For the nuclear decay hourglass, we also know similar things:

- present amounts in the top half (U in the zircon),
- the present trickling rate (nuclear decay rates), and
- the amounts in the bottom half (Pb isotopes in the zircon).

The large amount of He, the actual α-particles from the decays, confirms that a large amount of nuclear decay has taken place.

One way to reconcile these two hourglass readings is to suggest that one of them has a "valve" at its bottleneck controlling the trickling rate, a valve that was adjusted drastically in the past, either by natural mechanisms or possibly by direct intervention from God.

Some might want to imagine that the valve is on the He hourglass, and that for billions of years, diffusion rates were over 100,000 times slower until a few thousand years ago. In Sections 8 and 10, we discussed the possibility that *in situ* temperatures might have been low enough for long enough to accomplish that reduction by natural means. But we found that such scenarios (such as having "dry ice" temperatures deep underground for 1.5 billion years) do not seem at all feasible. In Appendix D we examine all the other conceivable natural ways we know of that the diffusion rates might have been much lower. None of them appears to be significant.

Another possibility is that God may have changed diffusion rates by some drastic means, say by adjusting the laws of atomic physics which control diffusion. But the laws of atomic physics also control the biochemical processes that sustain life. It is difficult to imagine (although God is not at all restricted by our weak imaginations) any such change in atomic physics that would have allowed life on earth to exist. Certainly the theorist would have a very large number of complicated consequences to explain.

On the other hand, it is much simpler to imagine that the valve is on the nuclear decay hourglass. Nuclear forces affect only a tiny region at the center of the atom. They have very little effect on the outer electronic structure of the atom or its chemical interactions. Moreover, a relatively small change in nuclear forces can cause a billion-fold acceleration of nuclear decay rates [*Chaffin*, 2000, 2003; *Humphreys*, 2000]. Finally, the preponderance of Biblical and geoscience evidence for a young world [*Humphreys*, 2000, pp. 337–339] points to a change that would only affect dating methods which depend on slowly-decaying nuclei.

Thus our new diffusion data support the hypothesis we proposed in our first book [*Vardiman*, 2000, pp. 3–5], that God drastically accelerated the decay rates of long half-life nuclei during the earth's recent past. For a feasibility study of this hypothesis—including God's possible purposes for such acceleration, Biblical passages hinting at it, disposal of excess heat, preserving life on earth, and effects on stars—see *Humphreys* [2000, pp. 333–379]. The last three problems are not yet fully resolved, but we expect to see progress on them in future papers. The next section gives some of our thinking about the heat problem.

13. Disposing of Excess Heat

In the previous RATE book [*Humphreys*, 2000, pp. 337, 369–370], my feasibility study of the accelerated decay hypothesis pointed out and discussed one of the obvious problems: nuclear decay generates heat! I wrote that without long periods of time in which the heat could dissipate by normal mechanisms, or without some new and faster mechanism, crustal rocks

> would melt many times over if decay rates were accelerated.

I also pointed out that heat is not merely a problem for accelerated decay, but also for all Creation or Flood models I know of.

> There is simply too much geological work to be done in too short a time. So the solution I outline here should be useful to *any* creationist geological model.

The RATE initiative has found several lines of evidence implying that *rapid cooling* occurred along with accelerated nuclear decay, resulting in a smaller rise of temperature than would have occurred without such cooling. Andrew Snelling's successful model for the formation of Po radiohalos requires rapid cooling. He and Mark Armitage concluded,

> … the timescale for cooling of the granitic plutons was also extremely short, measured in half-lives of these isotopes (days, not years) [*Snelling and Armitage*, 2003, p. 260].

John Baumgardner solved a long-standing geothermal mystery by assuming a burst of heat from accelerated decay accompanied by rapid cooling [*Baumgardner*, 2000, pp. 80–86]. In both these cases, most of the cooling could not be by the normal processes of conduction, convection, or radiation. Instead, the process would have to cool the entire volume of material simultaneously ("volume" cooling) and abnormally fast.

The diffusion data in this chapter imply that after the zircons acquired their He, they were never very much hotter than they are now, nor were they hot for very long. For a simplified illustration of this, imagine that the zircons experienced a high temperature T_h for a short time Δt, after which the temperature dropped abruptly to today's level, T, and remained at that level for a time t until now. Let us say that during the hot period, the zircons did not lose more than 30% of their He, thus having a retention fraction of 0.70. (Otherwise, t would have to be quite a bit less than 4000 years to allow the large retentions we observe.) Solving equation (14a) for a retention fraction Q/Q_0 of 0.70 gives us the value of x that would apply to the hot period:

$$x_h = 2.9169\times10^{-4} \tag{23}$$

Then equation (14c) gives us the diffusivity D_h required to retain 70%

of the He during time Δt:

$$D_h = \left(\frac{b}{\pi}\right)^2 \frac{x_h}{\Delta t} \tag{24}$$

Dividing equation (24) by a similar equation using D, x, and t gives us the ratio of the "hot" diffusivity D_h to today's diffusivity D:

$$\frac{D_h}{D} = \frac{x_h}{x}\frac{t}{\Delta t} \tag{25}$$

If today's diffusivity is on the "intrinsic" part of the curve, then we can use equation (2) and a little algebra to give us the temperature T_h during the hot spell in terms of the present temperature T:

$$T_h = \frac{T}{1 - \frac{RT}{E_0}\ln\left(\frac{x_h}{x}\frac{t}{\Delta t}\right)} \tag{26}$$

Here R is the universal gas constant, 1.986 cal/mol/K, and E_0 is the activation energy given in equation (5a). Let us take as an example the x-value and temperature (197°C = 470K) of point 3 in Table 3, and a t of 6000 years. Then for a Δt of 1 year, T_h would be about 90°C above today's temperature. For a Δt of 1 month, T_h would be about 140°C hotter than today. If the heat pulse had been much hotter or longer than those typical values, the diffusion age we calculate would have been significantly less than 4000 years, an age not correlating to any known geological event in the formation. In other words, our data and model are consistent with at most a short, moderate pulse of heating during and just after the accelerated decay episode.

It is very likely water was flowing through the cleavage planes of the biotite while it was hot [*Snelling*, 2005a, p. 133]. That would keep these zircons cooler than zircons in a material like tuff [*Snelling*, 2005b, p. 276ff] without clear channels for water flow. But probably that mechanism alone would not be enough to keep the temperature increase as low as 90°C. Also, the heat carried by the water has to go somewhere else on earth, and that heat would be more than enough to melt the earth's crust globally. Thus we require significant volume cooling to compensate for the otherwise large amount of heat from accelerated nuclear decay.

Now let us explore a way such volume cooling might occur. In my feasibility study, I pointed out [*Humphreys*, 2000, pp. 370–373] a little-known and less-understood phenomenon in standard General Relativity theory that seems quite relevant. The mechanism causes photons and moving material particles in an expanding cosmos to lose energy [*Robertson and Noonan*, 1968, pp. 343–344, 354–356; *Landau and Lifshitz*, 1983, pp. 374–375; *Ohanian and Ruffini*, 1994, pp. 582–583; *Rindler*, 2001, p. 369]. The equations clearly show the loss of energy, but where and how the energy goes is less clear. From the similarity of one of the equations to the thermodynamic conservation of energy in an expanding gas, Robertson and Noonan conclude (speaking of photons):

> Therefore, the radiation energy which is lost in an expanding universe is used up as work in aiding the expansion.

But they do not specify how. Other writers say even less, leaving even relativity experts in considerable confusion about whether the lost energy goes somewhere or simply disappears.

This mechanism offers good potential for removing heat on a large scale. We do not need to resolve the experts' confusion about where the energy goes in order to utilize this mechanism. However, for those who would like some understanding of the phenomenon, I offer the following very simplified explanation of my own.

If we take some Biblical and scientific clues seriously and think of space as being an actual but non-perceived *material* [*Humphreys*, 1994, pp. 66–68, 84, 89], then there is a way to understand the energy loss mechanism. Spacetime would be a "fabric" of three space dimensions and one time dimension, a deformable surface in a "hyperspace" of *four* space dimensions and one time dimension [*Humphreys*, 1994, pp. 93–96; *Humphreys*, 2002, pp. 100–101]. The fabric would be bent in the fourth (unperceived) direction with various curvatures. Particles can move along the surface unhindered, but the surface constrains the particles to follow curved paths conforming to the bends in the surface. For example, if the "fabric" constrains a particle of mass m moving with non-relativistic velocity v to follow a path whose radius of curvature is

R, as in Figure 19, then the particle will in turn exert a centrifugal force *F* on the fabric:

$$F = m\frac{v^2}{R} \tag{27}$$

This force would be in the direction of bending (the "*R*-direction") perpendicular to the surface of the "fabric," which as I implied above is a fourth spatial direction we cannot perceive directly. If the radius of curvature increases with a rate *R*, then the particle will lose kinetic energy *E* at a rate *E* given by the product of the force and the fabric's speed in the *R*-direction:

$$\dot{E} = -F\dot{R} = -m\frac{v^2}{R}\dot{R} \tag{28}$$

The dots signify the rate of change with respect to proper time (physical clock time) τ at the point in question. Dividing equation (25) by the kinetic energy gives us a simple result for the fractional loss rate:

$$\frac{\dot{E}}{E} = -2\frac{\dot{R}}{R} \tag{29}$$

In relativistic cosmologies, the fractional rate of change of the large-scale radius of curvature turns out to be the Hubble parameter *H*, so in that case equation (26) becomes

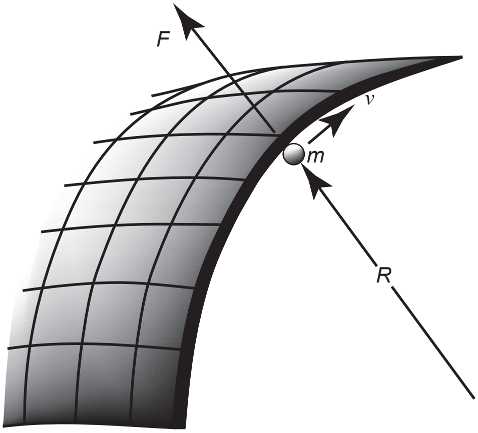

Figure 19. Particle motion in curved space.

$$\frac{\dot{E}}{E} = -2H \tag{30}$$

For photons and material particles of relativistic speeds, the result is similar, but with a different numerical factor. This result is exactly the same as the more rigorous general relativistic calculations give. This derivation shows us where the energy of a particle goes—it aids the expansion of the fabric, adding slightly to its kinetic energy. The particle and photon energy losses are by no means the main cause of the expansion, but the losses are very significant compared to their own energies. Eventually, the textbooks say, a free particle having mass will lose all its kinetic energy and come to rest relative to the "fabric."

Materialist academics will not like my derivation above because they do not like ascribing physical reality to "hyperspace" (although they do allow it as a mathematical convenience) or ascribing physical substance to spacetime. There appear to be deep-seated religious reasons for their dislike, as I pointed out in my cosmology book [*Humphreys*, 1994, pp. 94–95]. But, as I mentioned above, it is not necessary to accept my explanation to accept the loss mechanism itself.

As far as I can tell, the loss mechanism would apply not only to free particles, but also to particles under the influence of electromagnetic forces (such as forces between atoms), because such forces would operate entirely in the surface of the fabric, not adding vectorially to forces in the R-direction perpendicular to the surface. (The loss mechanism might not apply to particles orbiting in local gravitational fields, which come from local curvatures in the fabric superposed on the cosmic curvature [*Cooperstock et al.,* 1998].) That means that atoms and electrons moving thermally in a solid should also experience such a loss of kinetic energy, that is, thermal energy. If there were no other inputs or outputs of energy to or from the particles, the temperature T of the material would decrease in the same way as the energy in equation (30):

$$\frac{\dot{T}}{T} = -2H \tag{31}$$

When the other inputs and outputs of heat are significant, this equation would not apply. Instead, we would have to include equation (30) as one of the heat losses in the usual heat transport equations.

This mechanism would be insignificant if the Hubble parameter H has always had its present very small value. However, H would have a much higher value during periods of high time dilation, because it is the fractional rate of expansion as measured by *proper* time, time as measured by local, physical, clocks. In contrast, we would expect the rate of expansion to be governed by global parameters, which are in turn most closely related to ideal clocks synchronized with distant clocks. As a first approximation, we could say that the expansion rate as measured by distant clocks would be roughly constant during the periods of interest. But our local clocks would be very slow relative to distant clocks during periods of high time dilation locally, so the rate of expansion as measured by our local clocks would then be very large. As I suggested in my cosmology book [*Humphreys*, 1994, p. 68] and in my previous RATE chapter [*Humphreys*, 2000, pp. 367–368, 372–373], the Bible implies that two such episodes of expansion occurred, one during early Creation week and one during the Genesis Flood. These are the same two periods that seem most likely to have experienced accelerated nuclear decay, and there is probably a connection, as I pointed out [*Humphreys*, 2000, 367–369].

The fact that we see destructive events (apparently occurring after the Fall of Adam) in the distant cosmos would be explained by a manyfold (at least an order of magnitude) expansion/time-dilation episode during the year (as measured by our clocks) of the Genesis Flood. That would make H during the Flood billions of times higher than today's value, and we would easily be able to get rid of all the excess radiogenic heat.

The real problem is how to keep non-radioactive materials from getting *too cold* at the same time. I have not had time to pursue this part of the idea further, so here I can only outline a speculation that may turn out to provide a good explanation later.

If the "fabric" of space is a real material, as Scripture implies [*Humphreys*, 1994, pp. 67–68], then it must have a *temperature*. I speculate that its temperature might set a minimum on how much heat could be transferred to the fabric during rapid expansion. For example, equation (31) might become:

$$\dot{T} = -2H(T - T_{\min}) \tag{32}$$

where T_{min} is a minimum temperature that might depend on the amount of time dilation occurring at the moment. If T_{min} were about 300 K during the Genesis Flood, then creatures aboard the Ark could stay warm. Though this is sheer guesswork now, I am confident that a good explanation exists (whether or not we can find it). That is because (a) the evidence convinces me that accelerated nuclear decay did indeed occur, and (b) as one of Noah's descendants, I know that his family did not freeze to death aboard the Ark!

To summarize the heat problem, we have several lines of physical evidence for volume cooling having occurred, and there is at least one promising theoretical approach we can try. When we can devote more time to the problem, we may see good progress on it.

14. Conclusion

The experiments the RATE project commissioned have clearly confirmed the numerical predictions of our Creation model (updated slightly in Section 7), which we published beforehand [*Humphreys*, 2000, p. 348, Figure 7]. Other experimental data published since the beginning of our experiments agree with our data. The data also clearly reject the uniformitarian model. The data and our analysis show that over a billion years worth of nuclear decay has occurred very recently, between 4000 and 8000 years ago. This strongly supports our hypothesis of recent episodes of highly accelerated nuclear decay.

These diffusion data are not precise enough to reveal details about the acceleration episodes. Were there one, two, or three? Were they during early Creation week, after the Fall, or during the Flood? Were there only 500 to 600 million years worth of acceleration during the year of the Flood, with the rest of the acceleration occurring before that? We cannot say from this analysis. However, the fact that these zircons are from a Precambrian rock unit sheds some light on various creationist models about when strata below the Cambrian formed. We can say that the "diffusion clock" requires a large amount of nuclear decay to have taken place within thousands of years ago, after the zircons became solid. At whatever time in Biblical history Precambrian rocks came into existence, these data suggest that "1.5 billion years" worth of nuclear decay took place after the rocks solidified not long ago. Since the Phanerozoic strata usually give nuclear dates of 545 Ma or less, our zircons started accumulating He a significant time before the Genesis Flood began depositing the major fossil layers.

Previously we have presented the technical data in this chapter in three different scientific venues. The first was at the Fifth International Conference on Creationism in Pittsburgh, Pennsylvania, U. S. A., August 4–9, 2003, and archived in its *Proceedings* [*Humphreys et al.*, 2003a]. Then we presented new results in a poster and an abstract at the American Geophysical Union Annual Fall Meeting in San Francisco in December 2003, with the abstract being published in the *Transactions* of that organization [*Humphreys et al.*, 2003b]. Last, the *Creation Research Society Quarterly* documented the new data and results in its June 2004 issue [*Humphreys et al.*, 2004].

Our most important result is this: *He diffusion casts doubt on uniformitarian long-age interpretations of nuclear data and strongly supports the young world of Scripture.*

Acknowledgments

Many people and institutions have contributed to collecting and interpreting these data. In particular, we would like to express our appreciation to Robert Gentry for his seminal research and good advice, to Los Alamos National Laboratory for giving us the Fenton Hill samples, to Yakov Kapusta and Activation Laboratories, Ltd., for processing them, to Mark Armitage for his microscope work, to William (Bill) Hoesch for his laboratory work, to Roger Lenard and Majdah Al-Qutani of Zodiac Mining and Manufacturing, Inc., for its services as intermediary, and especially to the donors whose generosity made this work possible.

Appendix A: Isotopic Analysis of Jemez Zircons

Here we summarize a report by Dr. Yakov Kapusta (Activation Laboratories, Ltd., in Ontario, Canada) on an isotopic analysis he made on three zircons from Los Alamos National Laboratories core sample GT-2480 from borehole GT-2 in the Jemez granodiorite at a depth of 750 m. Dr. Kapusta separated zircons from the core sample using heavy liquids and magnetic separation. He picked three crystals from the zircon concentrate for analysis. Table A1 shows his results and notes.

Table A1. U-Pb analysis of three zircons from the Jemez granodiorite.

#	**Mass (μg)** (a)	**Concentrations**			**Ratios**			
		U (ppm)	**Pb (ppm)**	**Pb(com.) (pg)** (b)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ (c)	$\frac{^{208}\text{Pb}}{^{206}\text{Pb}}$ (d)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (e)	**Error (2σ%)**
z1	0.8	612	106.1	13.6	241.2	0.633	0.102828	.50
z2	1.0	218	59.6	1.4	2365.1	0.253	0.236433	.23
z3	1.7	324	62.7	1.7	3503.6	0.218	0.172059	.11

#	**Ratios**				**Ages**			
	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ **(e)**	**Error (2σ %)**	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ **(e)**	**Error (2σ %)**	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	**Correlation Coefficient**
z1	1.2744	.56	0.08989	.23	631.0	834.4	1423.2	0.912
z2	2.9535	.26	0.09060	.12	1368.1	1395.7	1438.2	0.887
z3	2.1456	.13	0.09044	.07	1023.4	1163.6	1434.9	0.828

Notes:

(a) Sample weights are estimated by using a video monitor and are known to within 40%.

(b) Total common-Pb in analyses

(c) Measured ratio corrected for spike and fractionation only.

(d) Radiogenic Pb.

(e) Corrected for fractionation, spike, blank, and initial common Pb.

Mass fractionation correction of 0.15%/amu±0.04%/amu (atomic mass unit) was applied to single-collector Daly analyses and 0.12%/amu±0.04% for dynamic Faraday-Daly analyses. Total procedural blank less than 0.6 pg for Pb and less than 0.1 pg for U. Blank isotopic composition: $^{206}\text{Pb}/^{204}\text{Pb} = 19.10\pm0.1$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.71\pm0.1$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.65\pm0.1$. Age calculations are based on the decay constants of *Steiger and Jäger* [1977]. Common-Pb corrections were calculated by using the model of *Stacey and Kramers* [1975] and the interpreted age of the sample. The upper intercept of the concordia plot of the $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{238}\text{U}$ data was 1439.3 Ma±1.8 Ma. (The published Los Alamos radioisotope date for zircons from a different depth, 2900 meters, was 1500±20 Ma [*Zartman*, 1979].)

Appendix B: Diffusion Rates in Biotite

Following are two reports by our diffusion experimenter (with our comments in brackets) on his measurements of He diffusion in biotite from two locations. As far as we know, these are the only He-in-biotite diffusion data that have been reported. The first sample, BT-1B, was from the Beartooth amphibolite near Yellowstone National Park. The second sample, GT-2, was from the Jemez granodiorite, borehole GT-2, from a depth of 750 m. The geology laboratory at the Institute for Creation Research extracted the biotite from both rock samples by crushing, density separation with heavy liquids, and magnetic separation. The experimenter sieved both samples to get flakes between 75 and 100 μm in diameter. Taking half of the average diameter to get an effective radius of 44 μm, we plotted the resulting diffusion coefficients for the GT-2 sample in Figure 9. We plotted the muscovite data in Figure 9 using the effective radius recommended in the report [*Lippolt and Weigel*, 1988], 130 μm.

Results of He Diffusion on Zodiac Biotite, BT-1B (Beartooth Amphibolite) October 18, 2000

Experiment:

Approximately 10 mg of biotite BT-1B, sieved to be between 75 and 100 μm, was subjected to step heating. Steps ranged in temperature from 50°C to 500°C in 50°C increments, with an estimated uncertainty on T of < 3ºC. Durations ranged from 6 to 60 minutes, with longer durations at lower temperatures; uncertainty on time is < 1% for all steps. After the ten steps the partially degassed biotite was fused to establish the total amount of He in the sample. Helium was measured by isotope dilution quadrupole mass spectrometry, with an estimated precision of 2%. Helium diffusion coefficients were computed using the equations of *Fechtig and Kalbitzer* [1966] assuming spherical geometry.

Data:

Table B1. Diffusion of He from biotite sample BT-1B

Step	Temperature °C	Minutes	Cumulative Fraction	ln e (D/a^2)
1	50	61	3.45E-06	-35.80
2	100	61	1.16E-04	-28.76
3	150	61	1.37E-03	-23.83
4	200	61	6.34E-03	-20.81
5	250	30	1.76E-02	-18.15
6	300	30	5.33E-02	-15.88
7	350	16	1.02E-02	-14.11
8	400	16	2.11E-01	-12.54
9	450	10	3.38E-01	-11.25
10	500	6	4.74E-01	-10.11
Remainder Fusion			5.26E-01	
Total			1.00000	

[In a later addendum to this report, the experimenter told us that the total amount of He liberated was about 0.13×10^{-9} cm^3 (at STP) per μg of biotite.]

Interpretation:

Helium diffusion from this biotite defines a remarkably linear Arrhenius profile, fully consistent with thermally activated volume diffusion from this mineral. The first two data points lie slightly below the array; this is a common feature of He release during step heating of minerals and has been attributed to "edge effects" on the He concentration profile [*Fechtig and Kalbitzer*, 1966; *Farley*, 2000]. Ignoring those two data points, the activation energy and diffusivity at infinite T based on these data are 25.7 kcal/mol and 752 [cm^2/sec] respectively. At a cooling rate of 10°C/Ma, these parameters correspond to a closure temperature of 39°C.

[After this the experimenter added a "Recommendations" section wherein he discussed the possibility of vacuum breakdown of the biotite at high temperatures, the relevant effective radius for biotite (probably half the sieved flake diameter), and the source of He in the biotite (probably U and Th in zircons that had been in the flakes before separation). We decided none of these questions were important enough to investigate in detail for now, since this sample was not from a site we were interested in at the time. It merely happened to be on hand at the Institute for Creation Research geology laboratory, making it ideal for an initial run to look for possible difficulties in experimental technique.]

Results of He Diffusion Experiment on Zodiac Biotite, GT2 [Jemez Granodiorite] March 24, 2001

Experiment:

Approximately 10 mg of biotite GT-2, sieved to be between 75 and 100 μm, was subjected to step heating. Steps ranged in temperature from 50°C to 500°C in 50°C increments, with an estimated uncertainty on T of <3°C. Durations ranged from seven to 132 minutes, with longer durations at lower temperatures; uncertainty on time is <1% for all steps. After eleven steps of increasing T, the sample was brought back to lower temperature, and then heated in six more T-increasing steps. After the seventeen steps the partially degassed biotite was fused to establish the total amount of He in the sample. Helium was measured by isotope dilution quadrupole mass spectrometry, with an estimated precision of 2% (steps 12 and 13 are much more uncertain owing to low gas yield). Helium diffusion coefficients were computed using the equations of *Fechtig and Kalbitzer* [1966] assuming spherical geometry.

Data:

See Table B2. [In a later addendum to this report, the experimenter told us that the total amount of He liberated was about 0.32×10^{-9} cm^3 (at STP) per μg of biotite.]

Interpretation:

Helium diffusion in this sample follows a rather strange pattern, with a noticeable curve at intermediate temperatures. I have no obvious explanation for this phenomenon. Because biotite BT-1B did not show this curve, I doubt it is vacuum breakdown. I ran more steps, with a

Table B2. Diffusion of He from biotite sample GT-2.

Step	Temperature °C	Minutes	Cumulative Fraction	ln e (D/a^2)
1	50	61	1.61E-05	-32.72
2	50	60	2.79E-05	-32.01
3	100	60	2.39E-04	-27.32
4	150	61	1.91E-03	-23.18
5	200	61	4.70E-03	-21.54
6	250	31	6.81E-03	-20.59
7	300	31	9.69E-03	-19.92
8	350	16	1.35E-02	-18.63
9	400	15	2.44E-02	-17.03
10	450	9	4.90E-02	-15.05
11	500	7	1.07E-01	-13.13
12	225	132	1.07E-01	-22.12
13	275	61	1.07E-01	-21.07
14	325	61	1.07E-01	-19.70
15	375	60	1.10E-01	-18.07
16	425	55	1.24E-01	-16.15
17	475	61	1.99E-01	-14.22
Fusion			8.00E-01	
Total			1.00000	

drop in temperature after the 500°C step, to see if the phenomenon is reversible. It appears to be, that is, the curve appears again after the highest *T* step, but the two steps (12, 13) that define this curve had very low gas yield and high uncertainties. It is possible that we are dealing with more than one He source (multiple grain sizes or multiple minerals?). [We think it is likely there were some very small He-bearing zircons still embedded in the biotite flakes, which would be one source. The other source would be the He diffused out of larger zircons no longer attached to the flakes.] This sample had about twice as much He as BT-1B. Note that despite the strange curvature in GT-2, the two biotite samples have generally similar He diffusivity overall.

[The similarity the experimenter remarks upon made us decide that the biotite data were approximately correct. Because these data below 300°C were also about an order of magnitude higher than our creation model, we supposed that zircon might be a more significant hindrance to He loss than biotite, so we turned our attention to zircon. It turned out that our supposition was correct, which makes it less important to have exact biotite data.]

Appendix C: Diffusion Rates in Zircon

Below is a report by the diffusion experimenter (again with our comments in brackets) on his measurements of He diffusion in zircons extracted by Yakov Kapusta from Los Alamos National Laboratories core sample GT-2480 from borehole GT-2 in the Jemez granodiorite at a depth of 750 m. Appendix A gives Kapusta's radioisotopic analysis of three of the zircons. The rest, unsorted by size and labeled as sample YK-511, were forwarded to the experimenter for diffusion analysis. In this chapter we call the sample "2002". In Figure 8 of this chapter, we assumed an effective radius of 30 μm (or length 60 μm) and plotted the points (numbers 15–44) which the experimenter concludes below are the most reliable. These points only go down to 300°C, but the later ones in Table 2 (sample 2003) go down to 175°C.

Report on Sample YK-511
[Jemez Granodiorite, sample 2002] May 14, 2002

We step heated 0.35 mg of zircons from the large vial supplied by Zodiac. We verified that the separate was of high purity and was indeed zircon. The step heat consisted of forty-five steps so as to better define the He release behavior. The first fifteen steps were monotonically increasing in temperature, after that the temperature was cycled up and down several times.

Results:

See Table C1. The first fourteen steps lie on a linear array corresponding to an activation energy of ~46 kcal/mol and a closure temperature of ~183°C assuming a cooling rate of 10ºC/Ma. However steps 15–44 [shown in Figure 8 of this chapter], which were cycled from low to high temperature and back, lie on a shallower slope, corresponding to $E_a = 34.5$ kcal/mol and $T_c = 128$°C. This change in slope from the initial

Table C1. Diffusion data for zircon sample YK-511.

Step	Temperature °C	Helium-4 (nnc)	Time (seconds)	Fraction	Cumulative Fraction	D/a^2 (sec^{-1})
1	300	5.337083	3660	0.001259	0.001259	3.78E-11
2	300	1.316732	3660	0.000311	0.001570	2.10E-11
3	300	0.935963	3660	0.000221	0.001791	1.77E-11
4	325	3.719775	3660	0.000878	0.002669	9.34E-11
5	350	7.910044	3660	0.001867	0.004536	3.21E-10
6	375	18.12294	3660	0.004278	0.008815	1.36E-09
7	400	36	3660	0.008498	0.017313	5.29E-09
8	425	73.10049	3660	0.017256	0.034569	2.13E-08
9	450	106.0761	3660	0.025040	0.059609	5.85E-08
10	460	78.89137	1860	0.018623	0.078232	1.27E-07
11	470	96.99925	1860	0.022897	0.101130	2.08E-07
12	480	117.2479	1800	0.027677	0.128807	3.40E-07
13	490	146.8782	1860	0.034671	0.163479	5.38E-07
14	500	171.5538	1800	0.040496	0.203976	8.46E-07
15	453	149.5962	7200	0.035313	0.239290	2.31E-07
16	445	66.45767	7260	0.015687	0.254978	1.16E-07
17	400	9.589814	6840	0.002263	0.257241	1.86E-08
18	420	10.64711	3600	0.002513	0.259755	3.98E-08
19	440	23.19366	3660	0.005475	0.265230	8.69E-08
20	460	52.3035	3660	0.012346	0.277577	2.05E-07
21	480	102.7062	3660	0.024244	0.301821	4.38E-07
22	325	0.357828	3660	8.45E-05	0.301906	1.61E-09
23	350	0.718240	3660	0.000170	0.302075	3.23E-09
24	375	1.690889	3660	0.000399	0.302475	7.62E-09
25	400	4.246082	3660	0.001002	0.303477	1.92E-08
26	425	8	3660	0.001888	0.305365	3.64E-08
27	450	21	3660	0.004957	0.310323	9.70E-08
28	460	22.0839	1860	0.005213	0.315536	2.05E-07
29	470	33	1800	0.007789	0.323326	3.26E-07
30	480	45	1860	0.010622	0.333948	4.47E-07
31	490	62.39899	1800	0.014729	0.348678	6.75E-07
32	500	82.65262	1800	0.019510	0.368189	9.59E-07
33	475	120.222	7260	0.028379	0.396569	3.80E-07
34	445	45	7260	0.010622	0.407191	1.53E-07
35	400	5.879406	7260	0.001387	0.408579	2.05E-08
36	300	0.075983	3660	1.79E-05	0.408597	5.26E-10
37	320	0.685076	21660	0.000162	0.408759	8.02E-10
38	340	1.122111	18060	0.000265	0.409024	1.58E-09
39	360	1.986425	14460	0.000469	0.409493	3.49E-09
40	380	3.413768	10860	0.000806	0.410299	8.01E-09
41	400	5.752365	7260	0.001357	0.411657	2.03E-08
42	420	6.126626	3660	0.001446	0.413103	4.30E-08
43	440	13.67016	3600	0.003226	0.416330	9.85E-08
44	460	30.37821	3660	0.007171	0.423501	2.19E-07

run-up to the main body of the experiment is occasionally observed and attributed to either:

(1) A rounded He concentration profile in the zircons, such that the initial He release is anomalously retarded. In other words, the He concentration profile is shallower than the computational model used to estimate diffusivities assumes. This effect goes away as the experiment proceeds and the effects of the initial concentration profile become less significant. This rounding could be due to slow cooling or possibly to recent reheating.
(2) The change in slope might be due to changes in the zircons during the heating experiment. For example, it is possible that annealing of radiation damage has occurred. This sample has a very high He yield (540 nmol/g) so radiation damage is likely. However the zircons were only marginally within the window where radiation damage is thought to anneal in zircons, so this hypothesis is deemed less likely.

Consideration of geologic history and/or further experiments are necessary to firmly distinguish between these possibilities.

Conclusion:

The most reasonable conclusion from the data is that the main body of the experiment, steps 15–44, yields the best estimate of the closure temperature, about 130°C. This is somewhat cooler than we have observed before in zircons though the database is not large. Radiation damage may be important in the He release kinetics from this He-rich sample.

[End of report by diffusion experimenter.]

Appendix D: Effects of the Interface and of Model Variations

Recently a critic sought very hard to find loopholes in our arguments. While his critique is unpublished and none of his points had any significant impact on our conclusions, it is worthwhile to review the specifics of his critique and answer them here. The critic felt a crucial issue was the possibility that the interface between zircon and biotite might slow or stop He diffusion because of He having different *chemical potentials* or *solubilities* in those two minerals, or because of *interface* *resistance* between them due to other causes. In the next three sections we will explain those terms and quantify their effects.

D.1 Differences in Chemical Potential

A diffusion theorist [*Manning*, 1968, section 5-3, p. 180, equation 5-36] expresses the *chemical potential*, μ, for He atoms constituting a fraction N of all the atoms in a crystal at temperature T as the sum of two parts:

$$\mu = kT \ln N + \mu' \tag{D1}$$

where k is the Boltzmann constant. The first term on the right, the "entropy of mixing," contains no information related to the forces between atoms. The second term, μ', is the one we are interested in. It is the contribution from all other factors, particularly the interaction energy between He and the other atoms of the crystal.

The same theorist [*Manning*, 1968, section 5-3, p. 180, equations 5-37 and 5-39] then expresses the flux J of He atoms in the x-direction through a region with diffusivity D as:

$$J = -D\frac{\partial C}{\partial x} - \frac{DC}{kT}\frac{\partial \mu'}{\partial x} \tag{D2}$$

The first term on the right represents ordinary diffusion. It is the second term that represents an additional flux due to a driving force, the gradient of μ'. This force originates in whatever chemical attraction the He atom might have for the atoms of the crystal in which it resides. Inside the crystal, these forces average to zero, but at the interface with another crystal, there may be a jump in μ'. If a He atom were to have greater chemical attraction for the atoms of zircon than for the atoms of biotite, that would result in a force at the interface hindering its outward motion into the biotite. The question we need to address is, "Just how great is the effect?"

Because He is one of the noble gases, we might suspect that it would have very little chemical attraction for any other atoms. In fact, He is the least chemically active of all the noble gases [*Holloway*, 1968,

p. 45, Table 2.1]. Nevertheless it does exhibit a faint attraction for other atoms. Theory and experiments [*Wilson et al.*, 1988, p. 936, Table XI] show that He atoms adhere very slightly to the surfaces of alkali halide crystals, with interaction potentials on the order of a few hundred calories per mole of He. The largest estimated potential is 293.4 cal/mol, at the "saddle point" between the Na and F ions at the surface of NaF. The smallest potential listed is beside a Cl ion at the surface of NaCl, 111.7 cal/mol.

The difference of those potentials provides an estimate of the difference of μ' at an interface between NaF and NaCl: 181.7 cal/mol, or 0.00788 eV per He atom. Because noble gases have a greater chemical affinity for halides [*Holloway*, 1968, p. 89] than for most other ions, the above number is almost certainly greater than the corresponding number for the silicate minerals we are considering. So at the interface between zircon and biotite, we can take the following value as a generous upper bound on the magnitude (absolute value) of the difference in μ':

$$\left|\Delta\mu'\right| < 0.0079\,\mathrm{eV/atom} \tag{D3}$$

Now we need to quantify the effect of that difference on the flux of He atoms in equation (D2). As we did in Sections 7 and 8, we assume for simplicity that the diffusivity D is the same for biotite as for zircon, and therefore constant across the interface. Because the observed value of C in the biotite is hundreds of times smaller than in the zircon (this chapter, Section 10), the magnitude of the change in concentration, ΔC, across the interface is nearly equal to the concentration C in the zircon:

$$\left|\Delta C\right| \approx C \tag{D4}$$

Assuming that the changes ΔC and $\Delta\mu'$ both occur within roughly the same small distance δx, the width of the interface, the He flux J in equation (D2) becomes:

$$J \approx -D\frac{\Delta C}{\delta x} - D\frac{\Delta C}{\delta x}\frac{\Delta\mu'}{kT} \tag{D5}$$

To make this mechanism a viable possibility for rescuing the uniformitarian scenario, the second term on the right-hand side must be: (1) of opposite sign to the first ($\Delta\mu'$ must be negative, meaning He is more attracted to zircon than biotite), and (2) large enough to reduce J to a level about 100,000 times lower than what the first term alone would give. That could reduce the He flow enough to let the zircon retain the He for 1.5 billion years. In the coolest sample we analyzed, at 100°C, the average thermal energy kT of the atoms was 0.0321 eV. Then $| \Delta\mu'/ kT |$ would be less than 0.246 for that sample, and even smaller for the hotter samples. That makes the magnitude of the second term less than 25% of that of the first term for all the samples we analyzed. However, our upper bound on the value of $\Delta\mu'$ based on the chemical affinity of He with alkali halides is likely at least an order of magnitude larger than the actual value. So a magnitude of the second term less than 2.5% of the first term is probably more realistic. The second term obviously does not provide the large reduction of He flow the uniformitarian scenario requires.

However, an even more basic consideration shows our measurement procedures have already accounted for such differences. We note that the magnitude of $\Delta\mu'$ is several times greater for a zircon-vacuum interface than for a zircon-biotite interface. That is, the attraction of a He atom for the biotite it is entering partly cancels its attraction for the zircon it is leaving. But our experimenter measured the diffusivities of zircons in a *vacuum*. So the zircon diffusivities we report in Table 2 already include the effect of a *stronger* interface reflection than would exist for the zircons in their natural biotite setting. So however strong or weak the "chemical potential" interface effect may be, our measured diffusivities already account for it in a way that is generous to the uniformitarian model.

D.2 Solubility

Solubility in this context corresponds to the maximum number of He atoms one gram of crystal can absorb per bar of pressure [*Weast*, 1986, p. 101]. The critic used the term as a measure of the difficulty with which a He atom could enter biotite. As a hypothetical example, if all the spaces between atoms in biotite were much smaller than the diameter of a He atom, then He could never enter the crystal, so He would be completely insoluble in biotite. If an α-decaying nucleus inside the biotite were to generate a He atom therein, then the atom could distort the lattice and push its way out. The crystal would have a small but non-zero He diffusivity and zero solubility.

However, real minerals have non-zero solubilities. The solubilities of He in obsidian and basaltic glass between 200° and 300°C, for example, are on the order of 50 nmol/g per bar [*Jambon and Shelby*, 1980, Figure 2c] and on the same order in other minerals [*Broadhurst et al.*, 1992]. The solubility of He in biotite has not been measured (we were the first to measure even diffusivity for that pair of substances), so we must find a way to estimate its effect in this case.

One way is to consider the interaction potential part μ' of the chemical potential we mentioned in the previous section. For a He atom near the surface of a crystal, the gradient of the potential is negative, making the force attractive. But the force can become repulsive for a He atom entering a tightly packed crystal. For example, imagine that a He atom has to come very close to an O atom. If their nuclei are closer together than 2.94 Å (1 Å = 1 angstrom = 1×10^{-8} cm ≈ diameter of a neutral H atom), the force between the two atoms is repulsive [*Kar and Chakravarty*, 2001, Table I, σ_{os} column and gradient of their equation 2].

However the space between silicate sheets in biotite is much larger than that [*Deer et al.*, 1962, Vol. 3, pp. 1–3, 55; *Dahl*, 1996, Figure 1 and Table 4]. The large spacing is the reason the diffusivity of He in biotite (section 5, Figure 9) is about ten times higher than in zircon, which has tighter spacing [*Deer et al.*, 1962, Vol. 1, pp. 59–68]. The relative spacings and diffusivities imply the solubility of He in biotite is greater than in zircon, so the force related to solubility, included in the gradient of μ', would tend to push He atoms out of zircon and into biotite. Hence their respective solubilities would not hinder He outflow from the zircon but rather enhance it.

D.3 Interface Resistance

Our critic also postulated some type of *interface resistance* arising from special distortion of the crystalline lattices at the interface between zircon and biotite. We can model such hypothetical interface resistance [*Crank*, 1975, p. 40, section 3.4.1] as a very thin layer of very low diffusivity between the zircon and biotite. The concentration of He would drop rapidly across the layer, approximating a discontinuous change of concentration between zircon and biotite. Such a layer might consist of physically or chemically altered zircon or biotite. Typical interface layers, such as oxides on metals, range from a few dozen angstroms to hundreds of angstroms in thickness.

Let us estimate how low the diffusivity D of the interface would have to be in order to retain the He in the zircon for 1.5 billion years. Since D is supposed to be much lower than the diffusivities of both zircon and biotite, we can approximate the situation as a hollow sphere with a wall of diffusivity D having an inner radius a and outer radius b. A source (representing nuclear decay) inside the sphere generates He at a steady rate q_0, and the He diffuses through the wall out into a vacuum outside the sphere. Textbooks show [*Carslaw and Jaeger*, 1959, section 9.2, p. 231, equation (7), $Q_0 \to q_0$, $K \to D$, $v_1 \to C$, $v_2 \to 0$] that the steady-state He outflow q_0 is

$$q_0 = 4\pi DC \frac{ab}{b-a} \tag{D6}$$

where C is the steady-state concentration of He inside the sphere. Taking the wall thickness δ ($b=a+\delta$) to be small compared to a ($\delta << a$), integrating q_0 for time t, and C over the sphere volume (Section 7, equation 16) gives us the ratio of He retained, Q, to total He generated, Q_0:

$$\frac{Q}{Q_0} \approx \frac{a\,\delta}{3D\,t} \tag{D7}$$

Turning this around gives us the interface diffusivity D required to retain a fraction Q/Q_0 of He for time t in a zircon of effective radius a

surrounded by an interface of thickness δ:

$$D \approx \frac{a\,\delta}{3(Q/Q_0)\,t} \tag{D8}$$

For example, with a (large) interface thickness of 300 Å, $a = 30\,\mu\text{m}$, and a time of 1.5 billion years, the 17% retention of sample 3 requires an interface diffusivity of

$$D \approx 3.8\times10^{-25}\ \text{cm}^2/\text{sec} \tag{D9}$$

This is over *one billion times lower* than the diffusivities we measured in biotite (Section 5, Figure 9) and zircon (Section 5, Figure 8) at the same temperature, 197°C. To see whether this is an achievable value or not, let us examine an example the critic gave for physical alteration of the minerals at the zircon-biotite interface.

The critic suggested that when biotite crystallizes around a zircon, it possibly forms with its silicate sheets (along which are the cleavage planes) everywhere parallel to the surface of the zircon, so that the biotite wraps up the zircon like layers of cellophane. But in the hundreds of thousands of zircon-containing biotite flakes that we ourselves have observed under the microscope [*Snelling and Armitage*, 2003; *Snelling et al.*, 2003; *Snelling*, 2005a], the silicate sheets remain parallel all the way to the edge of the zircon crystal and do not wrap around the included zircons. A Los Alamos report has a photo of a radiohalo in biotite from borehole GT-2 showing the biotite cleavage staying parallel to itself, running right up against the zircon, and not becoming parallel to the zircon surface [*Laughlin and Eddy*, 1977, Figure 6, p. 18]. There is simply no observational support for the critic's hypothesis that layers of biotite totally envelop an included zircon.

However, for the sake of having a specific illustration of interface resistance, let us indulge the critic and imagine that a few dozen of the biotite layers closest to the zircon wrap around it, having a total interface thickness of 300 Å. We will even imagine that there are no openings in the biotite wrapping at the edges and corners of the zircon faces. In that case, diffusion in the interface would have to take place in the harder direction, perpendicular to the silicate sheets rather than parallel to them.

Let us estimate the diffusivity in that harder direction. Measurements show that in biotite, "Ar diffusion is ~500 times faster parallel to the silicate sheets than perpendicular to the silicate sheets" [*Onstott et al.*, 1991, section 7, p. 166]. Because a He atom has a smaller diameter, 2.28 Å, than an Ar atom, 3.35 Å [*Kar and Chakravarty*, 2001, Table I; σ_{ss} column], then for He there should not be as great a difference between "parallel" diffusivity $D_{||}$ and "perpendicular" diffusivity $D_{\perp}$. So for He in biotite, the ratio $D_{||}/D_{\perp}$ should be less than 500. Our measurements for He in biotite (Section 5, Figure 9) gave, for example, $D_{||} = 8.6 \times 10^{-15}$ cm²/sec at 200°C. Dividing that diffusivity by 500 gives us a lower bound on the diffusivity in the difficult direction:

$$D_{\perp} > 1.7 \times 10^{-17}\ \mathrm{cm^2/sec} \tag{D10}$$

That is over *40 million times greater* than the maximum diffusivity, equation (D9), that a 300 Å interface could have and still retain the He for 1.5 Ga. Hence such a hypothetical mechanism fails to account for the high He retention we document. Moreover, as we have already indicated, there is no observational support for the sort of interface crystallographic structure our critic speculates might exist.

D.4 Effects of Model Assumptions

The critic also explored the effects of several changes in the assumptions of our models:

(1) inserting a large interface resistance,
(2) increasing the Creation model D for biotite to infinity,
(3) decreasing the uniformitarian model D for biotite from infinity down to that of zircon,
(4) accounting for anisotropy of biotite and zircon, and
(5) changing the effective radius a from our early value of 22 μm [*Humphreys*, 2000, p. 347] to our more recent and more appropriate value of 30 μm (Section 7, after equation 9).

We have discussed change (1) in the preceding section, showing that it is unrealistic. Change (2) increases the He loss rate from the zircons by a factor of six, making it less realistic than our assumption, which had a worst-case effect of 30% (Section 7, after equation 9). Change (3) decreases the loss rate from zircons by a factor of six, but we think it is unrealistic for uniformitarians to demand an extremely low value of *D* for the biotite as well as the zircon.

Regarding mineral anisotropies (4), we point out two things:

- switching from sphere to cylinder geometry (roughly approximating anisotropy effects) for the most important mineral (zircon) would alter the results by less than a factor of two, and
- even a factor-of-ten reduction in the modeled diffusivity of the surrounding mineral (biotite) would change our results by less than 30% (Section 7, after equation 9). Thus, accounting for biotite anisotropy would affect our results by much less than 30%.

As for zircon, anisotropy in it is probably just as negligible as it is in many other similarly shaped crystals, such as quartz. Both our experimenter and other diffusion experts have not assigned a high priority to investigating that possibility.

Change (5), the increase in effective radius *a* required by our better knowledge of zircons, by itself would have increased the model-required *D*'s by a factor of about two. But our better knowledge also required another model change, from a "bubble" in biotite to a solid in biotite. This second change reduced the *D*s by about a factor of two. Because the two effects nearly cancelled each other out, the *net* change in predicted *D* was less than 0.5%. We explained these things in our Fifth International Conference on Creationism paper [*Humphreys et al.*, 2003a, section 6], but perhaps not clearly enough.

The critic acknowledged that changes (2–5) would not come anywhere close to eliminating the 100,000-fold discrepancy between our data and any reasonable uniformitarian scenario. But he asserted that the several-fold sensitivity to changes in assumptions means that the close agreement between the Creation model and the data was merely accidental. That may be a possibility, but it may also mean we exercised good theoretical judgment in choosing the simplifying assumptions for our prediction.

D.5 Closing Criticisms

Finally, the critic proposed we postpone publication until (a) further theoretical and experimental investigations would close all alleged loopholes, and (b) until we have much more data supporting our case from boreholes all over the world. We disagree with him. On point (a), detractors can allege loopholes eternally, and we think we have addressed all the so-far-alleged loopholes well enough to place the burden of proof on the detractors.

On point (b), the critic was not clear as to what he meant. If he wanted diffusion rate data on zircons from more sites, it is doubtful that such data would be much different than what we measured. Our zircon data give essentially the same intrinsic parameters, E_0 and D_0, as those of several other experimenters (Section 5, Figure 8). As for the defect parameters, E_1 and D_1, there is no reason to expect them to generally give defect lines more than one or perhaps two orders of magnitude different from ours. That is because the radiation levels in our zircons are fairly typical (in contrast to those of Magomedov, see our Section 4). Defect lines for zircons at future sites would have to be more than five orders of magnitude lower than ours in order to have even a chance of rescuing the uniformitarian scenarios.

Possibly the critic meant his point (b) to imply that the high He retentions in the Jemez granodiorite could be unusual, so we would need to do similar studies on a large amount of sites to assure ourselves that high retentions are normal. Of course it would be good to do more such studies, but we feel that the data in this chapter are so well established that it would be wrong to withhold them for the several years required for other site studies. In fact, our data here may stimulate more such studies.

As an encouragement to creationists considering such work, we offer the following opinion: *high He retentions are probably the rule*, not the exception. Otherwise the large amount of geoscience literature reporting great (U-Th)/He chronometry ages (Section 9) would not exist. That is because the method essentially divides the amount of He retained by today's nuclear decay rate, so large retentions of He are necessary to get great ages. If their zircons had lost most of their He by diffusion, their dates would be in great disarray, and usually rather young. Because their zircons are often of similar size as ours [*Reiners*, 2002], the He loss rates will be similarly fast. That suggests young diffusion ages such as ours will turn out to be common.

I would like to take this opportunity to thank Roger Lenard, a physicist at Sandia National Laboratories in Albuquerque, New Mexico, for his expert advice on chemical thermodynamics, which helped me to prepare Sections D2 and D3 above.

Endnotes

i Uniformitarianism is the conscious or unconscious assumption that “all continues just as it was from the beginning” [2 Peter 3:4], omitting the possibility of any large-scale physical interventions by God into the natural realm. Often scientists do this because, whether they are aware of it or not, they have accepted “methodological naturalism,” the incorrect teaching that scientists must ignore scientific evidence for non-natural phenomena. The teaching is incorrect because such an *a priori* naturalism would lead to incorrect interpretations of the data if God has in fact intervened in the natural world in a way that leaves physical evidence of the intervention. Many uniformitarians interpret scientific data to support their preconception of cosmic and biological evolution occurring during supposed billions of years. Such interpretations misunderstand clear observational data all around us [*Humphreys*, 2000, p. 339]. The Bible predicted [2 Peter 3:5–6] that a time would come when many thinkers would ignore “elephant in the living room” evidence for a recent Creation and a worldwide catastrophic Flood.

ii Note that the large retentions are not what uniformitarian geoscientists mean by “excess He” [*Baxter*, 2003]. In the context of these zircons, “excess” He would correspond to retentions *greater than 100%* of the amount nuclear decay could produce in 1.5 Ga. We are not claiming such “excess” He at all. The uniformitarian method of “He dating,” called *(U-Th)/He chronometry* [*Reiners*, 2002] is entirely different from the He *diffusion* dating we are employing here. (See endnote iv.) (U-Th)/He chronometry would not call attention to the large He *retentions* we are concerned with (in fact, it depends upon large retentions, Appendix D, section D4), so it may turn out that sites like borehole GT-2 are common throughout the world.

iii Half the cited 2σ experimental reproducibility error of 6% in D/a^2 gives us a 1σ error of ±3%. I estimate the 1σ error in the average value of a^2 for these size-selected zircons is less than ±10%. A possible shape factor error [*Fechtig and Kalbitzer*, 1966, p. 72, Section 2.4] for the shape distribution in our Figure 1 could add a 1σ error in a^2 of ±25%. (I measured the length/width ratio of each zircon in Figure 1 and used the resulting ratios in this analysis.) That error is systematic, shifting the whole $D(T)$ curve up or down by the same factor. Also, it cancels itself out in comparisons with the predictions based on the same value of a^2 for crystals of the same size from the same site. But here I will regard it as random. Taking the square root of the sum of the squares of those errors gives us 27.0%, which I round upward to 30%. So in Table 2, multiplying D/a^2 in column 6 by a^2 gives values of the diffusivity D in column 7 whose 1σ error I estimate as ±30%.

iv Our diffusion dating method in Section 9 differs entirely from the “He dating” of (U-Th)/He chronometry [*Reiners*, 2002]. Very crudely, the difference is this: (U-Th)/He chronometry divides the number of He atoms *in* a crystal by *nuclear* decay rate. Diffusion dating divides the number of He atoms *lost* from the crystal by the *diffusion* rate. Some practitioners of (U-Th)/He chronometry, in their unpublished comments about our work, have not yet understood this distinction.

v Because b is nominal and ultimately cancels itself out of the analysis (see paragraph under equation (7) in Section 7), the 1σ error bounds on D/b^2 in equation (17) are the same as those of D/a^2, ±3%, as Endnote iii above shows. The error for extrapolation between data points with the curve fit is smaller than that. The effects of those errors are small compared to the effect of the (assumed 1σ) ±30% error in Q/Q_0 on x in Table 3 and equation (17). The resulting bounds on x (and D) in samples 2–4 of Table 3 (the age calculation does not use sample 1 and the error in sample 5 is indeterminate) average out to ±32%. That correlates well with the error of ±(2000 years/6000 years) = ±33% from the statistics of the individual age calculations in Table 5.

vi The probability that a single data point could be separated by more than 25 standard deviations on a given side away from the mean of the normal distribution governing the data is less than 6×10^{-8} [*Abramowitz and Stegun*, 1967, p. 933, equation (26.2.25), using $1 - P_4(x)$ and $x = 25$].

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