



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 ncc = 10^{-9}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 1 σ error in D is less than $\pm 30\%$ (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.

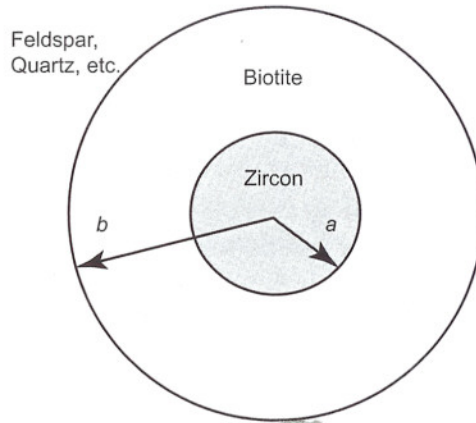


Figure 12. Spherical approximation of the zircon-biotite system.

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):

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

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:

$$b \approx 1000 \mu\text{m} \quad (7)$$

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 $0.32 \times 10^{-9} \text{ cm}^3$ STP (standard temperature and pressure) per microgram (μg). Taking into account the difference in density of biotite and zircon (3.2 g/cm^3 and 4.7 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 $r = b$:

$$C(b) = 0 \quad (8)$$

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:

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

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:

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

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:

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

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:

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

where we define the function S_n as follows:

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

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

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

$$\text{and } x = \frac{\pi^2 Dt}{b^2}$$

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 $\pm 30\%$ 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 $\pm 5\%$) 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 $\pm 30\%$ error completely dominates.

Table 3. New Creation model.

Sample	T (°C)	Q/Q_0	x	D (cm ² /sec)	1 σ Error (%)	
1	105	0.58 \pm 0.17	5.9973 \times 10 ⁻⁴	3.2103 \times 10 ⁻¹⁸	+122	-67
2	151	0.27 \pm 0.08	2.4612 \times 10 ⁻³	1.3175 \times 10 ⁻¹⁷	+49	-30
3	197	0.17 \pm 0.05	4.0982 \times 10 ⁻³	2.1937 \times 10 ⁻¹⁷	+39	-24
4	239	0.012 \pm 0.004	3.3250 \times 10 ⁻²	1.7798 \times 10 ⁻¹⁶	+33	-18
5	277	\sim 0.001	1.8190 \times 10 ⁻¹	9.7368 \times 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 120°C 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 190°C 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:

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

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:

$$\frac{Q}{Q_0} = \frac{a^2}{15Dt} \quad (16)$$

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 = 4.7×10^{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 (°C)	Q/Q_0	D (cm ² /sec)	1 σ 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 $\pm 2\sigma$ error bars on both models and data in the figure). The data points extend past the “knee” of the model at 197°C (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

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

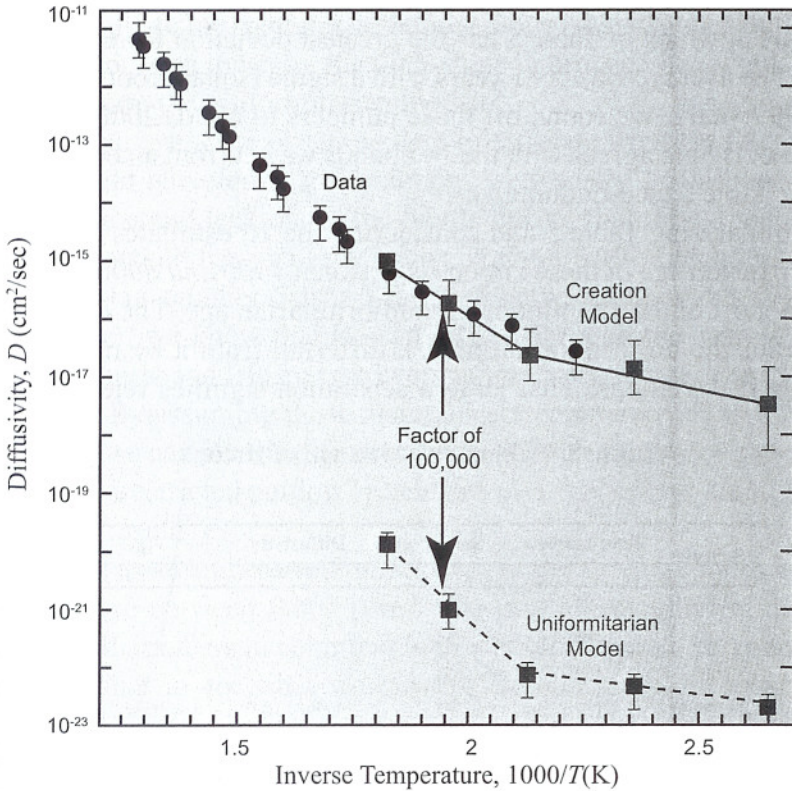


Figure 13. The 2003 zircon data line up very well with the Creation model, and they resoundingly reject the uniformitarian model. The ordinate is D (not D/a^2). Error bars show $\pm 2\sigma$ bounds on data and models.

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 (cm ² /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 (°C)	Measured D/a^2 (sec ⁻¹)	Helium Retentions Q/Q_0	
			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 = $10^{-9} \text{ cm}^3 \text{ STP} = 0.4462 \times 10^{-4}$ nanomole), or 6.05×10^{-2} nmol (1σ error $\pm 3\%$). Dividing by the mass ($\pm 1\%$) gives us 6.28 ncc/ μg , or 303 nmol/g ($\pm 3\%$). Multiplying the latter value by the density of zircon, 4.7 g/cm^3 ($\pm 2\%$), gives us the He concentration in the zircon: 1320 nmol/cm^3 ($\pm 4\%$).

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

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 ($\pm 30\%$) estimate of radiogenic He deposited in the zircons, $15 \text{ ncc}/\mu\text{g} \pm 30\%$ (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 $\pm 30\%$ 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 $\pm 3\%$ (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 $124 (\pm 1)^\circ\text{C}$. 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