Evaluation of the Ar/Ar Dating Process

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Abstract

During the last half of the twentieth century, the argon-argon method of dating geologic rocks and formations became very popular. This method replaced K/Ar as the method of choice for many types of rocks. This paper explores the fundamental mathematics of the argon-argon dating method and evaluates the impact of the assumed date of the "standard sample" on the calculated argon-argon date. A method for testing the validity of an argon-argon date is proposed with example evaluations. The analysis in this paper shows that when the results of dating studies are validated against the foundational equations upon which the argon-argon dating method is based, the "older" the standard sample the greater the results differ from the foundational equations. This seems to indicate that the assumed age of the standard sample has an effect on the calculated age of the unknown sample. The paper proposes a way to further investigate and quantify the effect of the assumed age of the standard sample.

Introduction

The decay of radioactive potassium (^{40}K) to stable argon (^{40}Ar) was first used to attempt to measure the age of rocks in the 1940s. This dating technique is called the potassium-argon (K/Ar) dating method, and it became one of the preeminent radiometric dating techniques for dating rocks that are believed to be in the Cenozoic and earlier geologic layers. While a detailed discussion of the history of K/Ar dating is beyond the scope of this paper, McDougall and Harrison (1999; e.g., chapter 1) provides a brief but thorough overview of the history of K/Ar and argon-argon ($^{40}Ar/^{39}Ar$) dating.

As the K/Ar dating method was being developed, it became obvious that there is a problem with "excess Ar." Analysis of the phenomenon of excess Ar appeared in the literature in the 1960s. For example, Damon et al. (1967, p. 463) state, "It now appears that some level of excess ^{40}Ar in minerals is a ubiquitous phenomenon." It is the continued problem of excess ^{40}Ar that has caused some scientists to question the validity of the K/Ar dating method itself (e.g., Austin, 1996; Snelling, 1998)

In the 1960s, while investigations into the excess ^{40}Ar phenomenon were getting started, Merrihue and Turner (1966) pioneered a variation of the K/Ar dating method that utilized the ability to produce ^{39}Ar from ^{39}K with neutron interaction. This variant is called the $^{40}Ar/^{39}Ar$ dating method. Over time, the $^{40}Ar/^{39}Ar$ method has become preferred over the K/Ar method.

A point of interest is that the $^{40}Ar/^{39}Ar$ method relies on the use of a fluence monitor sample (also called the standard sample). The fluence monitor sample is a rock of "known age" that is irradiated with the unknown sample. In most cases, the "known age" of the fluence monitor sample is determined by the K/Ar dating method.

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This leads to a fundamental question that needs to be explored. That is, what effect, if any, does the "known age" of the fluence monitor sample have on the calculated age of the unknown sample? Another question to address is how young-earth creation scientists can use the naturally occurring phenomenon of radioactive decay to study the earth's history from a Biblical perspective. Both of these questions are explored in this paper.

Ar/Ar Dating Equations

McDougall and Harrison (1999) provide a detailed derivation of the equations used for $^{40}Ar/^{39}Ar$ dating. The final equation for the age of the unknown sample is shown in equation 1 (equation numbers in brackets are those given in the cited source). "λ is the constant of proportionality known as the decay constant, which is the probability of any particular atom decaying per unit time. Thus the decay constant can be thought of as the fraction of parent radioactive atoms decaying per unit time" (McDougall and Harrison, 1999, p. 17).

(1) [2.16] $t=(1/\lambda)\ln(1+J(^{40}Ar^{*}/^{39}Ar_{K}))$,

where:

t=sample age

λ = decay constant = $5.543(\pm0.010)\times10^{-10}\ a^{-1}$ (for ^{40}K)

J=Irradiation Parameter (explained below)

$^{40}Ar^{*}$ = Radiogenic Argon formed from ^{40}K decay in nature

$^{39}Ar_{K}$ = Argon 39 produced from ^{39}K by fast neutron irradiation

McDougall and Harrison (1999) provide the following equation for J:

(2) [2.14] $J=\dfrac{^{39}K}{^{40}K^{*}}\dfrac{\lambda}{\lambda_{e}+\lambda_{e}'}\Delta\int\phi(E)\sigma(E)dE$,

where:

^{39}K and $^{40}K^{*}$ = the amount of each potassium isotope

$\dfrac{\lambda}{\lambda_{e}+\lambda_{e}'}$ = Ratio of relevant partial decay constants to the decay constant (λ) of ^{40}K (As the reader will see below, this term is not important because it is replaced with another term later).

Δ = Duration of exposure to neutron radiation

$\Phi(E)$ = Neutron flux at energy E in units of neutron-cm/(cm^{3}sec-erg)

$\sigma(E)$= Neutron capture cross section at energy E

McDougall and Harrison (1999) then substitute Equation 3 for J, stating that the above parameters are difficult to measure:

> Because of the difficulties encountered in accurately determining the relevant integrated fast-neutron dose a sample has received, Merrihue and Turner (1966) suggested that a mineral of accurately known K/Ar age be irradiated together with the unknown to monitor the dose. (p. 18)

(3) [2.18] $J'=((e^{\lambda t'})-1)/(^{40}Ar^{*}/^{39}Ar_{K})'$

Unfortunately, McDougall and Harrison (1999) do not adequately differentiate between the terms related to the fluence monitor sample of "known age" and the sample of unknown age. To help in this area, I will assign the (‘) symbol to terms related to the fluence monitor sample of "known age." Various authors use different notations, so I will convert all equations to a standard notation, where (‘) refers to values related to the fluence monitor sample of "known age" and terms without the (‘) refer to values related to the sample of unknown age. There is also a difference among authors for the convention of identifying isotopes. Some authors put the mass number in superscript before the chemical symbol (^{40}K), while others put the mass number in superscript after the chemical symbol (K^{40}). I will convert all equations to the convention of putting the mass number in superscript before the chemical symbol.

The use of J' as given by McDougall and Harrison (1999) is described below.

> As the age *t*(‘) of the standard sample is known from conventional K/Ar age measurement, the parameter *J* can be determined from eq. (2.18) [my equation 3] by simply measuring the $^{40}Ar^{*}/^{39}Ar_{K}$(‘) ratio in the gas extracted from the standard sample after irradiation. This value of *J* is then used in eq. (2.16) [my equation 1], together with the $^{40}Ar^{*}/^{39}Ar_{K}$ ratio measured on the unknown sample irradiated at the same time, so that the sample age can be determined. (p. 19)

Therefore, the date of the unknown sample is calculated by using equations 1 and 3. Table I provides the various forms of equations 1 and 3 that will be used throughout this paper. The table provides the equation number and the equation. Equations 1 and 3 are repeated in the table in the appropriate place.

Note that McDougall and Harrison (1999) rely upon the equivalence of J and J', but they do not demonstrate that equivalence. Their justification for doing so is referencing Merrihue and Turner (1966). There is nothing wrong with this, but we must now turn our attention to Merrihue and Turner.

Merrihue and Turner (1966) begin their derivation with equation 8 below. In Equation 8, τ (tau) is the "mean life," which is the half-life divided by 0.693. The half-life is assumed to be constant with a current value of 1.25×10^{9} years. Equation

Table I. Ar/Ar Dating Equations

Eq. #	Sample of Unknown Age
1	$t=(1/\lambda)\ln(1+J(^{40}Ar^*/^{39}Ar_K))$
	λ (constant) = $5.543X10^{-10}$ ^{40}K
4	$J=((e^{\lambda t})-1)/(^{40}Ar^*/^{39}Ar_K)$
5	$(^{40}Ar^*/^{39}Ar_K)=((e^{\lambda t})-1)/J$
	Fluence Monitor Sample of "Known Age"
3	$J'=((e^{\lambda t'})-1)/(^{40}Ar^*/^{39}Ar_K)'$
6	$t'=(1/\lambda)\ln(1+J'(^{40}Ar^*/^{39}Ar_K)')$
7	$(^{40}Ar^*/^{39}Ar_K)'=((e^{\lambda t'})-1)/J'$

8 is, then, the foundation for the justification of the equivalency of J and J'. It is noted that J' as developed from equation 8 and the J needed in equation 1 are not mathematically equivalent. Instead, they are treated as functionally equivalent. That is, J' can serve the same function as J even though it is not mathematically equivalent.

$$(8)\quad [1]\ (^{40}Ar/^{40}K)/(^{40}Ar/^{40}K)'=$$
$$(^{40}Ar/^{39}Ar_k)/(^{40}Ar/^{39}Ar_k)'=$$
$$(^{41}Ar/^{39}Ar_k)/(^{41}Ar/^{39}Ar_k)'=((e^{t/\tau})-1)/(e^{t'/\tau})-1)$$

By way of explanation, the isotopes ^{41}Ar and ^{39}Ar are produced by neutron irradiation of the sample in a nuclear reactor. The ^{41}Ar results from ^{40}Ar present in the sample by absorption of a neutron and emission of a gamma ray photon. The ^{39}Ar results from ^{39}K by the reaction of absorption of a neutron and emission of a proton. The probabilities of these reactions are known quantities, given by a so-called neutron-absorption cross section. Under the conditions assumed by Merrihue and Turner (1966), all of the ratios given in the above equation must be equal. Hence, by assuming a known value for the age t', Merrihue and Turner's hypothesis enabled the calculation of the age t of the unknown sample.

Proposed Ar/Ar Dating Validation

Since equation 8 is the foundation for accepting the functional equivalency of the J factors, this equation can be used to validate the results. The two relevant terms from equation 8 are shown in equation 9. The left side of equation 9 will be referred to as the "Ar Ratio," and the right side of equation 9 will be referred to as the "Age Ratio."

$$(9)\quad (^{40}Ar/^{39}Ar_k)/(^{40}Ar/^{39}Ar_k)'=((e^{t/\tau})-1)/(e^{t'/\tau})-1)$$

It should be noted that equation 9 uses ^{40}Ar while equations 5 and 7 use radiogenic $^{40}Ar^*$. However, this is merely a difference in naming convention as Merrihue and Turner (1966, p. 2853) state, "For the sake of convenience we shall refer throughout the paper to all argon other than Ar^{39} ($^{39}Ar_k$) and radiogenic Ar^{40} ($^{40}Ar^*$) as contamination."

Each of the terms in equation 9 is input to, or derived from the $^{40}Ar/^{39}Ar$ dating process. Therefore, the data from the analysis can be used to calculate both the Ar ratio and the age ratio. For the calculated date of the unknown sample to be valid, the equality of equation 9 must be satisfied within statistical significance. If the Ar ratio and age ratio are not statistically equal, then some part of the analysis is incorrect. Generally, it should be either the assumed "known date" used for the fluence monitor or the calculated date of the unknown sample.

Validation Analysis

Renne et al. (1997) dated lava from the AD 79 eruption of Mt. Vesuvius using the $^{40}Ar/^{39}Ar$ dating method. This study is interesting because it is often referenced as being an example of the accuracy of $^{40}Ar/^{39}Ar$ dating. Table II provides information based on the data reported by Renne et al. (1997). The data in Table II is straightforward except for the value for the age of the unknown sample (the Vesuvius lava) "t." In their study, Renne et al. (1997) report an $^{40}Ar/^{39}Ar$ isochron age of 1925 ± 94 years, which is remarkable because the eruption occurred 1918 years before the analysis. However, this age is obtained by excluding the argon from the first two heating steps. They specifically state:

> Because there is no objective basis for excluding the lowest temperature steps, we prefer the isochron obtained from all 46 analyses as the best estimate of the age of this sample. The presence of extraneous ^{40}Ar is substantiated by the total gas results; the $^{40}Ar/^{39}Ar$ apparent age calculated from the sum of all gas released is 3300 ± 500 years, clearly distinct within error from the known calendar age. (Renne et al., 1997, p. 1297)

For this paper, I will use the 3300-year total gas date. The data are reported by Renne et al. (1997) as the mean age of

Table II. Mt. Vesuvius Data

Data	Source
t=3300	Renne, et. al.
$J=J'=1.413X10^{-5}$	Renne, et. al.
$t'=1.19X10^{6}$ years	Renne, et. al.
$(^{40}Ar^*/^{39}Ar_K)'=4.67X10^{1}$	Equation 7
$(^{40}Ar^*/^{39}Ar_K)=1.29x10^{-1}$	Equation 5

Table III. Detailed calculation

Term	$({}^{40}Ar^{*}/{}^{39}Ar_{K})'$	$({}^{40}Ar^{*}/{}^{39}Ar_{K})$
λ	$5.543X10^{-10}$	$5.543X10^{-10}$
t	$1.19X10^{6}$	3300
λt	0.000660331	0.00000182919
$e^{\lambda t}$	1.00066055	1.00000182919
$e^{\lambda t}-1$	0.00066055	0.00000182919
J	$1.413x10^{-5}$	$1.413x10^{-5}$
$(e^{\lambda t}-1)/j$	46.75	0.129

multiple samples of the Mt Vesuvius lava irradiated at the same time. Since they do not all give the exact same age, ± one standard deviation of the ages is reported to identify the variation. For the calculations below, I will simply use the mean value. Table III provides the detailed calculations for the last two terms of Table II.

From Table II, we can see that we have enough information to evaluate equation 9. Substituting the data from Table II into the left side of equation 9, we get a value for the Ar ratio as shown in Equation 10.

$$(10)\quad ({}^{40}Ar/{}^{39}Ar_{k})/\ ({}^{40}Ar/{}^{39}Ar_{k})'= 1.29x10^{-1}/4.67X10^{1}=2.76X10^{-3}$$

Substituting from Table II into the right side of Equation 9 we get a value for the age ratio as shown in equation 11.

$$(11)\quad ((e^{t/\tau})-1)/(e^{t'/\tau})-1)=((e^{(3300/1.25X10^{\wedge}9)}-1) /((e^{(1.19X10^{\wedge}6/1.25X10^{\wedge}9)}-1)=2.64X10^{-6}/9.52X10^{-4} =2.77X10^{-3}$$

Within rounding error, equation 9 seems to be valid at least to 3 significant figures. It is noted that if the 1925 date is used in equation 11 rather than the 3300 date, equation 11 equals $1.62X10^{-3}$ which is not equal to equation 10. Therefore, the 3300 date for the Mt. Vesuvius lava is more correct and the ${}^{40}Ar/{}^{39}Ar$ dating process gave a date that is 72% higher than it should be.

Evaluating the Influence of the Fluence Monitor Age

Since J and J' are not mathematically equal but are used as functionally equal, the next question is, to what extent does the age of the fluence monitoring sample affect the calculated ${}^{40}Ar/{}^{39}Ar$ age? The Mt. Vesuvius analysis adds credence to this question. For this analysis, the researchers did not use the standard fluence monitors that are considered to be tens or hundreds of millions of years old. Instead, they chose a fluence monitor that is considered to be 1.19 million years old. During their discussion of the laboratory procedures, Renne et al. (1997, p. 1280, emphasis added) state: "Finally, the use of an *appropriately aged* (Quaternary) neutron fluence monitor…" (emphasis added). What does "appropriately aged" mean, and is that why they used a younger-than-normal fluence monitor?

Dalrymple et al. (1993) performed an analysis of sedimentary rocks in the Beloc Formation, Haiti. The important thing about this study is that they dated the same material using three different fluence monitors and two different laboratories. Of interest to this paper are the different fluence monitors.

At the beginning of their discussion of the monitor material, Dalrymple et al. (1993) make the following comment:

> The ${}^{40}Ar/{}^{39}Ar$ ratios for the monitor minerals are used along with their known age to calculate a conversion efficiency factor, J, which is a measure of the fraction of ${}^{39}K$ converted to ${}^{39}Ar$ by the fast neutron reaction ${}^{39}K(n,p){}^{39}Ar$. J is then used in the age equation to calculate the age of the unknown samples. The calibration of the monitor minerals, therefore, has a direct effect on the accuracy of the ${}^{40}Ar/{}^{39}Ar$ ages calculated for the unknown sample. … In addition, there is not universal agreement on the ages used for the monitor minerals, and different laboratories, including Menlo Park and Denver, sometimes use slightly different values (ages) for the same monitor mineral (pp. 6, 7).

Table IV gives the details about the three monitor minerals used by Dalrymple et al. (1993)

While they used three fluence monitors, they only report data on two of the monitors (MMbh-1 and Taylor Creek Rhyolite [TCR]) in their paper. Table V shows the calculation of the Ar ratio and age ratio for each of the samples reported in Table II of Dalrymple et al. (1993). Table V also includes the above Mt. Vesuvius (MV) calculation for comparison. Table V has the irradiation number, sample number, sample material, and monitor mineral as reported by Dalrymple et al. (1993). Following this header information is the calculation of the Ar ratio, which is shown in the first gray boxes. The age ratio is

Table IV. Fluence Monitors

Name	Age
Fish Canyon Tuff Sanidine	27.55 Ma
Taylor Creek Rhyolite	27.92 Ma
MMhb-1 Hornblende	513.9 Ma

shown in the second gray box. Table V is shown in two parts to fit on the page.

From inspection of Table V, it is seen that while the Ar and age ratios are generally close, they are not equal. The bottom row of Table V is a calculation of the % error using equation 12.

(12) % Error = (Ar Ratio-Age Ratio)/Ar Ratio*100

Comparison of Means

While the Ar ratio and the age ratios in Table V are not the same, we need to perform a comparison-of-means test to determine if the difference is statistically significant. The comparison-of-means test used is described in Mendenhall and Sincich (1989). Tables VI and VII provide the comparison-of-means calculations. Since the Mt. Vesuvius analysis only involved one data point, a comparison of means is not useful. Therefore, the comparison of means is performed on the other two studies from Table V.

The purpose of the comparison of means is to see if the difference in the average Ar ratio and the average age ratio for each of the fluence monitors (MMhb-1 and TCR) is statistically significant. From Table V, we see that there are two data sets for MMhb-1 and 11 data sets for TCR. In both cases small sample statistics are used to perform the test.

From Table VII, we see that the T-stat is greater than the

Table V. Calculation of Ar and Age Ratios for Dalrymple et. al. and Mt. Vesuvius data

Irradiation	GLN3-1	105-1	105-2	105-3	108-1	JD06-1	JD08-1
Sample #	90G15K	90G15K	90G15K	JFL-500C	JFL-500C	83-O-05	83-O-05
Sample Material	Haiti Tektites	Haiti Tektites	Haiti Tektites	Z-Coal Bentonite Sandine	Z-Coal Bentonite Sandine	Z-Coal Bentonite Sandine	Z-Coal Bentonite Sandine
Monitor Mineral	MMhb-1	TCR	TCR	TCR	TCR	TCR	TCR
lambda(λ)	5.54E-10	5.54E-10	5.54E-10	5.54E-10	5.54E-10	5.54E-10	5.54E-10
t'	5.14E+08	2.79E+07	2.79E+07	2.79E+07	2.79E+07	2.79E+07	2.79E+07
$\lambda t'$	0.2849	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155
$e^{(\lambda t')}$	1.3296	1.0156	1.0156	1.0156	1.0156	1.0156	1.0156
$e^{(\lambda t')}-1$	0.3296	0.0156	0.0156	0.0156	0.0156	0.0156	0.0156
J	0.004376	0.010398	0.010452	0.010452	0.009474	0.006862	0.006910
$(^{40}Ar/^{39}Ar)'$	75.3128	1.4999	1.4922	1.4922	1.6462	2.2729	2.2571
Average $(^{40}Ar/^{39}Ar)$	8.4331	3.5784	3.5672	3.5264	3.9478	5.3816	5.4098
Ar Ratio	0.1120	2.3857	2.3906	2.3632	2.3981	2.3678	2.3968
Tau (τ)	1.25E+09	1.25E+09	1.25E+09	1.25E+09	1.25E+09	1.25E+09	1.25E+09
t	6.45E+07	6.44E+07	6.44E+07	6.44E+07	6.52E+07	6.45E+07	6.45E+07
t/τ	0.0516	0.0515	0.0515	0.0515	0.0522	0.0516	0.0516
$e^{(t/\tau)}$	1.0529	1.0529	1.0529	1.0529	1.0535	1.0530	1.0529
$e^{(t/\tau)}-1$	0.0529	0.0529	0.0529	0.0529	0.0535	0.0530	0.0529
t'/τ	0.4111	0.0223	0.0223	0.0223	0.0223	0.0223	0.0223
$e^{(t'/\tau)}$	1.5085	1.0226	1.0226	1.0226	1.0226	1.0226	1.0226
$e^{(t'/\tau)}-1$	0.5085	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226
Age Ratio	0.1041	2.3411	2.3411	2.3411	2.3705	2.3444	2.3429
% Error	7.044%	1.870%	2.070%	0.937%	1.148%	0.985%	2.248%

(table continues on next page)

Table V (continued)

Irradiation	108-2	108-3	JD06-2	JD08-2	GLN3-2	105-4	MV
Sample #	90G15K	90G15K	90G15K	90G15K	JFL-500C	JFL-500C	
Sample Material	Haiti Tektites	Haiti Tektites	Haiti Tektites	Haiti Tektites	Z-Coal Bentonite Sandine	Z-Coal Bentonite Sandine	
Monitor Mineral	TCR	TCR	TCR	TCR	MMhb-1	TCR	
lambda(λ)	5.54E-10	5.54E-10	5.54E-10	5.54E-10	5.54E-10	5.54E-10	5.54E-10
t’	2.79E+07	2.79E+07	2.79E+07	2.79E+07	5.14E+08	2.79E+07	1.19E+06
λt’	0.0155	0.0155	0.0155	0.0155	0.2849	0.0155	0.0007
$e^{(\lambda t')}$	1.0156	1.0156	1.0156	1.0156	1.3296	1.0156	1.0007
$e^{(\lambda t')}$-1	0.0156	0.0156	0.0156	0.0156	0.3296	0.0156	0.0007
J	0.009452	0.009495	0.006862	0.006910	0.004404	0.010322	0.0000
$(^{40}Ar/^{39}Ar)'$	1.6501	1.6426	2.2729	2.2571	74.8340	1.5110	46.6974
Average $(^{40}Ar/^{39}Ar)$	3.9914	3.8938	5.3875	5.5703	8.3400	3.5820	0.1290
Ar Ratio	2.4189	2.3705	2.3704	2.4679	0.1114	2.3706	0.00276247
Tau (τ)	1.25E+09	1.25E+09	1.25E+09	1.25E+09	1.25E+09	1.25E+09	1.25E+09
t	6.45E+07	6.45E+07	6.45E+07	6.45E+07	6.45E+07	6.45E+07	3.30E+03
t/τ	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	2.64E-06
$e^{(t/\tau)}$	1.0529	1.0529	1.0529	1.0529	1.0529	1.0529	1.0000
$e^{(t/\tau)}$-1	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	2.64E-06
t’/τ	0.0223	0.0223	0.0223	0.0223	0.4111	0.0223	0.0010
$e^{(t'/\tau)}$	1.0226	1.0226	1.0226	1.0226	1.5085	1.0226	1.0010
$e^{(t'/\tau)}$-1	0.0226	0.0226	0.0226	0.0226	0.5085	0.0226	0.0010
Age Ratio	2.3429	2.3429	2.3429	2.3429	0.1041	2.3429	0.00277179
% Error	3.141%	1.163%	1.156%	5.063%	6.603%	1.168%	-0.338%

Table VI. Comparison-of-means data

Ar Ratio	Mean	Std. Dev. (s)	n	s^2
MMhb-1	0.1117	0.000373366	2	1.39402E-07
TCR	2.3910	0.030623973	11	0.000937828
Age Ratio				
MMhb-1	0.1042	0	2	0
TCR	2.3451	0.008511482	11	7.24453E-05

Table VII. Comparison of means calculation

Comparison of Means Calculation	MMhb-1	TCR
Pooled Estimate of Variance (s_p^2)	6.97011E-08	0.000505137
SQRT($s_p^2(1/n_1+1/n_2)$)	0.00026401	0.009583476
y_1-y_2	0.0075	0.0459
df (n_1+n_2-2)	2	20
$t_{\alpha/2}$@ 95% confidence	4.303	2.086
t stat (Do=0)	28.52916064	4.786635516

$t_{\alpha/2}$ @ 95% confidence. Therefore, we can conclude that the differences in the mean are statistically significant to the 95% confidence level, so the underlying assumption of equation 9 is not met. This means that J and J' are not equal and the dates calculated for the unknown samples are not valid. With only one data point, we cannot draw conclusions about the difference in the means of the Mt. Vesuvius analysis.

Age/Error Relationship

Table VIII shows the average % error along with the "known age" of the fluence monitor for all 3 data sets. The fluence monitor for the Mt. Vesuvius study was Adler Creek sanidine (ACs).

From Table VIII, it appears that the older the assumed age of the fluence monitor, the greater the average error between the Ar and age ratios. At first glance it may seem that the % error is low, which validates the process. However, keep in mind that the error is the differences in the mean value of two sets of values that are supposed to be equal to one another. Therefore, the % error, by itself, does not provide enough information to determine if the values are in fact equal. The previous section provided the statistical comparison of the means to show that the values are not equal and the process is not valid. Graph 1 is the same data as in Table VIII along with a linear regression analysis trend line. From Graph 1, we see that there is a strong correlation between the assumed age of the fluence monitor and the % error. This indicates that the older the assumed age of the fluence monitor, the less valid the ages calculated from the process.

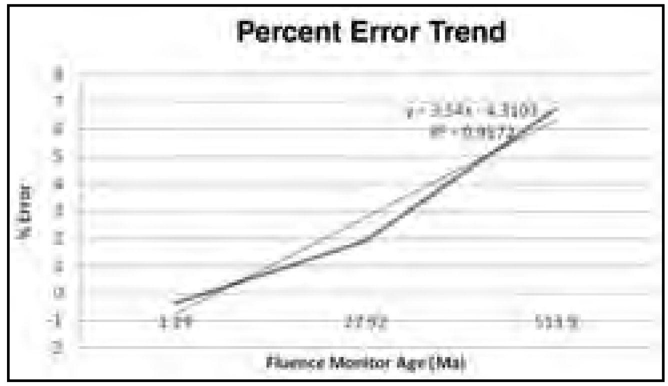
It should be noted that the first point in Graph 1 is from a different unknown sample, a different fluence monitor, and a different laboratory than the other two points. The other two points have the same unknown sample in common but use different fluence monitors and different laboratories. While these differences in the sources of the data can be problematic, the differences also make the high correlation more remarkable.

Proposed Follow-up Research

This study begins to show that $^{40}Ar/^{39}Ar$ dating may not be as valid as an absolute dating technique as some would like.

Table VIII. Average Error

Monitor	Age (Ma)	Avg % Error
ACs	1.19	-0.338
TCR	27.92	1.905
MMhb-1	513.9	6.742



Graph 1. Percent error between the Ar and Age Ratios for various fluence monitors

There appears to be a relationship such that the older the assumed date of the standard sample, the more the results err from the foundational equations. This relationship needs further exploration.

This could be done by irradiating a sample of unknown age with multiple fluence monitors of different assumed orders-of-magnitude ages in the same reactor at the same time. If the fluence monitor has an effect, the calculated age should be statistically significantly different. This will allow us to determine if there is a pattern to this relationship and possibly quantify the differences, which may lead to ways to calibrate $^{40}Ar/^{39}Ar$ dates from a young-earth perspective.

The value of this research to the young-earth community is that radioactive decay is a naturally occurring phenomenon. As such, we should be able to find a way to properly use this to make scientific discoveries about the age of the earth within the context of Scripture. The RATE project initiated this approach. They found that "one fundamental conclusion is that radioactive half-lives have not remained constant throughout the earth's history" (DeYoung, 2005, p. 142). The proposed research may continue down the road of discovery and quantification of those changes.

Conclusions

A method for validating $^{40}Ar/^{39}Ar$ dates was introduced and used to show that the $^{40}Ar/^{39}Ar$ dates obtained by Dalrymple et al. (1993) are not valid. There also appears to be a problem with the assumed age of the fluence monitor affecting the calculated age of the unknown sample. The observed relationship is that the older the assumed age of the fluence monitor, the greater the percent error of the analysis. The ability of $^{40}Ar/^{39}Ar$ dating to provide absolute ages is questionable.

A side conclusion is that claims that the Mt. Vesuvius analysis of Renne et al. (1997) demonstrates the accuracy of

^{40}Ar/^{39}Ar dating are not correct. This study gave a date that is 72% older than the known eruption date.

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References

Austin, S. A. 1996. Excess argon within mineral concentrates from the New Dacite Lava Dome at Mount St. Helens volcano. *Journal of Creation* 10(3):335–343.

Dalrymple, G. B., G. A. Isett, L.W. Snee, and J.D. Obradovich. 1993. ^{40}Ar/^{39}Ar age spectra and total-fusion ages for tektites from Cretaceous-Tertiary boundary sedimentary rocks in the Beloc Formation, Haiti. *U.S. Geological Survey Bulletin* 2065, United States Government Printing Office, Washington DC.

Damon, P.E., A.W. Laughlin, and J.K. Percious. 1967. Problem of excess argon-40 in volcanic rocks. In *Radioactive Dating and Methods of Low-Level Counting*, pp. 463–481. International Atomic Energy Agency, Vienna, Austria.

DeYoung, D. 2005. *Thousands Not Billions*. Master Books, Green Forest, AR.

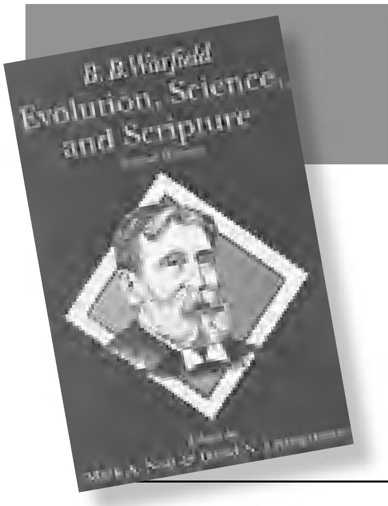
McDougall, I., and T.M. Harrison. 1999. *Geochronology and Thermochronology by the ^{40}Ar/^{39}Ar Method*, 2nd Edition. Oxford University Press, New York, NY.

Mendenhall, W., and T. Sincich.1989. *A Second Course in Business Statistics: Regression Analysis*, 3rd Edition. Collier Macmillian, London, UK.

Merrihue, C., and G. Turner. 1966. Potassium-argon dating by activation with fast neutrons. *Journal of Geophysical Research* 71:2852–2857.

Renne, P.R., W.D. Sharp, A.L. Deino, G. Orsi, and L. Civetta.1997. ^{40}Ar/^{39}Ar dating into the historical realm: calibration against Pliny the Younger. *Science* 277:1279–1280.

Snelling, A. A. 1998. The cause of anomalous potassium-argon "ages" for recent andesite flows at Mt. Ngauruhoe, New Zeland, and the implications for potassium-argon "dating." In Walsh, R.E. (editor), *Proceedings of the Fourth International Conference on Creationism*, pp 503–525.Creation Science Fellowship, Pittsburgh, PA.



Book Review

Evolution, Science, and Scripture: Selected Writings of B. B. Warfield

edited by Mark Noll and David Livingstone

Baker Books, Grand Rapids, 2000, 347 pages, $24.00.

Twenty-first-century creation scientists will be pleasantly surprised at what they may learn from a nineteenth-century theologian who accepted Darwinism. Considering Warfield's acceptance of both Darwinism and Christianity as a model to emulate in our own day, Noll and Livingstone have reprinted a great number of his relevant book reviews and essays. Their notes, as well as the introductory essay, help the reader understand Warfield's context. Notwithstanding the editors' purpose, many of his observations, which this review will highlight, are critical of Darwinism.

This book is a sequel to the authors' reprint of Charles Hodge's rebuttal of evolution (1994) and Noll's earlier work (1983) on Princeton Theological Seminary (PTS). According to Hodge, Warfield's predecessor at Princeton, Darwinism was atheism because it denied teleology. Wells (1996) reviewed this Hodge reprint from the intelligent design perspective. A strong defender of Biblical inerrancy, Warfield was professor of theology at Princeton from 1887 until his death in 1921. On a personal note, my grandfather, a PTS alumnus of that era, likewise held a high view of Scripture, though he opposed Darwinism. Dembski (2001) provided a recent perspective on PTS from the intelligent design perspective.

In the real world, Warfield observed, there is no such thing as an objective scientific voice. Instead there are the many voices of subjective scientists (p. 329). Science should be in submission to Biblical revelation: "Science is not fact, but human reading of fact; and any human reading of fact may well bow humbly before the reading given by God" (p. 174). Concerning certain books promoting Darwinism, he wrote that if these authors hadn't assumed evolution in the first place, then it wouldn't have appeared in their conclusions (p. 184). Though Darwinists appeal to lots of time to bring about development, time itself is not a sufficient cause (pp. 228, 274). Another perceptive comment is that survival of the fittest may be only a "theory that fits in best with the presuppositions and prejudices of the times" (p. 264).

Similar comments to Warfield's in 1916 could be repeated in the twenty-first century: "We are rather surprised to find Mr. Shearman still operating with the embryonic-recapitulation theory … We have supposed that this notion had been long since exploded" (p. 320).

Commenting on Hubrecht's research that primates did not form easily into a phylogenetic tree, Warfield wrote that giving "the lines of descent more and more the aspect of parallel lines is certainly not to say that the progress of research is in the direction of establishing the original evolutionary assumption" (pp. 185–186). In fact, this evidence appears to support the young-earth hypothesis of original *baramins* having only limited development. Warfield's observation is similar to the often-suggested creation "orchard."

Though natural selection worked on the stream of descent, it didn't produce it in the first place (p. 239). Concerning abiogenesis, Warfield questioned how the earliest environment could produce an organism out of adaptation to itself (pp. 266–267). He also wondered why a tolerable adaptation hadn't been reached long ago, so that evolution should have ceased. Devoid of the observation of facts, theories of evolution have a highly speculative character. He wrote that Darwinism itself suggests the need of a miracle (p. 244, 256). Again he questioned the notion that scientists are objective seekers of truth: "It almost seems at times that facts cannot be accepted unless a causo-mechanical theory be ready to account for them. This looks amazingly like basing facts on theory rather than theory on facts" (p. 246).

Warfield's 1888 lecture at PTS expounded the following reasons to doubt evolution, which students could nevertheless accept (pp. 122–125): (1) Darwin defended his theory against the fossil record rather than using it as positive evidence. (2) Embryonic development shouldn't keep the variations from past generations since these are no longer found in the fetus. Therefore the embryonic recapitulation argument for evolution is illogical. (Recent studies also demonstrate that early proponents of this theory falsified the evidence.) (3) There is not enough time for evolution, undoubtedly based on Kelvin's arguments from global and solar cooling (pp. 40, 225, 275). Though since then some question Kelvin's estimates because of additional terrestrial heat from nuclear processes, Slusher and Gamwell (1978) argue that heat from this source is not sufficient and therefore this argument for a young earth stands. (To my knowledge neither side has quantified this, however.) (4) There are observed limits to biological change at present. (5) Phylogenesis parallels these limits (e.g. Hubrecht's primates mentioned above).

Though Warfield believed in an old earth, in 1903 he acknowledged that "students of the Bible" and "Bible readers at large" dated the creation of the globe to only a few thousand years ago (pp. 216–217, 271). He didn't mention the teachings of Seventh-Day Adventists (SDAs). This constitutes additional evidence against the mistaken hypothesis of Noll and other historians that evangelical belief in a young earth is derived from SDAs. Warfield contrasted the Biblical Fall of man from innocence into transgression with the evolutionary rise of man to morality. For evolution, the Fall, instead of being a crisis of morality, was a condition of morality (pp. 128–129).

Warfield challenged Robinson's idea that the soul was latently present in the original creation, emerging without divine intervention (p. 290). In 1905, James Orr mentioned the impossibility of the disparate development of man's mind and body. Therefore it is not feasible that man's body developed by the accumulation of small mutations from a brute and that the soul was created all at once by divine fiat for the physically completed man (pp. 232–233). Warfield responded that this objection might not hold against a theory of evolution by leaps (the punctuated equilibrium theory). However, when Orr stated that no Scripture teaches that animals suffer death because of man's sin, Warfield responded that the creation being cursed for man's sake and which will be delivered with man from the bondage of corruption [Romans 8:19–22] might be evidence for this position (p. 236).

Denying the supernatural, some scientists were enemies of Christianity (p. 327) in Warfield's day: "Any science which leaves no place for these facts [miracles] as such is not neutral but antagonistic to Christianity, and between that science and this religion there must be no eternal peace but eternal war."

The Anglican clergyman and scientist John Polkinghorne (1999), whom Noll and Livingstone consider a follower of Warfield (p. 15), opposed him, however, on this crucial point. Warfield noted that evolution is a philosophy of the universe allowing only natural causes and "has no claim to be called science" (pp. 130–131, 160–161.)

Reviewing Shearman's assertion that although Darwin didn't demonstrate how evolution occurred, he had proved it did occur, Warfield rejoined that if the method of evolution wasn't proven, then evolution itself wasn't yet proven (p. 319). His argument is still useful today in light of the conflicting ideas on how evolution occurred, whether by a neo-Darwinian slow and gradual change, by leaps (punctuated equilibrium), or by a quasi-pantheistic symbiosis.

Darwinism was not immune from critical examination in Warfield's class. His pedagogy was to "teach the controversy." Evangelicals tempted to accept evolution should consider Machen's prescient warning that naturalism, discontented with occupying Christianity's lower sphere (origins), forces its way into the citadel (denying the deity and miracles of Christ). Creation scientists concur with Noll and Livingstone, however, that Warfield was a worthy example in that he critically examined evolution and taught the surprisingly still relevant scientific evidence against it.

References

Dembski, William and Richardson (editors). 2001. *Unapologetic Apologetics*. InterVarsity Press, Downers Grove, IL.

Hodge, Charles. 1994. *What Is Darwnism?* Edited by M. Noll and D. Livingstone. Baker, Grand Rapids, MI. (Orig. pub. 1874).

Noll, Mark (editor and compiler). 1983. *The Princeton Theology: 1812–1921*. Baker, Grand Rapids, MI.

Polkinghorne, John. 1999. Statement that God may not intervene in the cosmos because this would be "capricious," Theology and the New Physics conference at Calvin College, April 16. Grand Rapids, MI.

Slusher, Harold, and Thomas Gamwell. 1978. *The Age of the Earth*. Technical Monograph No. 7. Institute for Creation Research, El Cajon, CA.

Wells, Jonathan. 1996. Politically dead wrong. *Origins & Design* 17:2. Also online at http://www.arn.org.

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Book Review

Our Created Moon: Earth's Fascinating Neighbor

by Don DeYoung and John Whitcomb

Master Books, Green Forest, AR, 2010, 94 pages, $16.00.

This colorful book is an updated version of DeYoung and Whitcomb's previous book with the same title. This edition contains 46 questions divided into five sections, each dealing with a different aspect of the moon's special place in creation. Topics include the history of the moon and moon references in Scripture. One of the most interesting sections concerns the many purposes of the moon. This includes the importance of our moon to life on earth. For example, the moon protects the earth from space collisions, provides an energy source for the ocean currents, and is the main cause of the tides. In addition, the moon provides light for the earth at night and has provided calendar systems throughout history. These are just some of the many vital purposes the moon serves for humanity.

Scattered throughout the book are vocabulary words, fun facts, moon activities, and suggestions for further study. It has the potential to be used at home or in school as an educational resource. There are many beautiful pictures of the moon, as well as tables and diagrams that make the answers easy to understand. There are two appendices that focus on observing the moon and possible future space travel to the moon. An index, glossary of terms, and list of references located in the back complete the book.

This book maintains the strong dedication to Scripture and the understandable writing style of the earlier edition and will be a valuable asset to anyone interested in learning more about our very different yet very special neighbor, the moon.

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