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Recalibrated Legacy $^{40}\text{Ar}/^{39}\text{Ar}$ Ages for the Upper Jurassic Morrison Formation, Western Interior, U.S.A.

Kelli C. Trujillo¹ and Bart J. Kowallis²

¹Uinta Paleontological Associates, Inc., Laramie, WY 82070; kellitrujillo@icloud.com

²Department of Geological Sciences, Brigham Young University, Provo, UT 84602; bkowallis@byu.edu





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Editors

Douglas A. Sprinkel
Utah Geological Survey
801.391.1977
dsprinkel@gmail.com

Bart J. Kowallis
Brigham Young University
801.422.2467
bkowallis@gmail.com

Thomas C. Chidsey, Jr.
Utah Geological Survey
801.537.3364
tomchidsey@utah.gov

Steven Schamel
GeoX Consulting, Inc.
801.583.1146
geox-slc@comcast.net

Production

Cover Design and Desktop Publishing
Douglas A. Sprinkel

Cover Photograph

Morrison Formation near Notom looking towards the east with the Henry Mountains in the far background. The upper Salt Wash and colorful Brushy Basin Members of the Morrison can be seen in the foreground with the Cedar Mountain Formation and Mancos Shale above. The Tidwell and lower Salt Wash Members are not seen in the photo. Photograph by Bart J. Kowallis.



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Recalibrated Legacy $^{40}\text{Ar}/^{39}\text{Ar}$ Ages for the Upper Jurassic Morrison Formation, Western Interior, U.S.A.

Kelli C. Trujillo¹ and Bart J. Kowallis²

¹Uinta Paleontological Associates, Inc., Laramie, WY 82070; kellitrujillo@icloud.com

²Department of Geological Sciences, Brigham Young University, Provo, UT 84602; bkowallis@byu.edu

ABSTRACT

As a result of recent updating of decay constants and standard ages used for $^{40}\text{Ar}/^{39}\text{Ar}$ dating, it is necessary to recalibrate legacy ages obtained with older methods. These recalibrations bring legacy $^{40}\text{Ar}/^{39}\text{Ar}$ ages into better agreement with ages obtained using $^{238}\text{U}/^{206}\text{Pb}$ dating methods. We present nine recalibrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the Upper Jurassic Morrison Formation of the Western Interior, U.S.A., along with the individual geographic and stratigraphic locations for each sample. These recalibrated ages will be useful for researchers looking to place better age constraints on the flora and fauna of the Morrison Formation, as well as for those working to understand stratigraphic relationships across the formation. The recalibrated ages also can now be used reliably for comparisons with newer $^{238}\text{U}/^{206}\text{Pb}$ ages obtained for the Morrison Formation.

INTRODUCTION

The Upper Jurassic Morrison Formation is one of the most-studied rock units in North America. Its vertebrate fauna includes fish, amphibians, reptiles, and mammals. Dinosaurs from the Morrison Formation are exhibited in many museums worldwide and are among the best-known and loved dinosaurs in the public imagination.

The Morrison Formation was deposited under terrestrial conditions, mainly on floodplains, in river channels, and in small lakes as well as small dune fields in some areas. The formation is exposed across the Western Interior of North America, and it is generally recognizable across this depositional area. In the areas of the northern Colorado Plateau where this study is focused, three formal members are recognized: the lower Tid-

well Member, the middle Salt Wash Member, and the upper Brushy Basin Member. On the southern part of the Colorado Plateau other members are recognized in the lower parts of the formation, whereas in the northern and eastern parts of the depositional area no formal members are recognized (Turner and Peterson, 1999). Correlations across this large area can be problematic due to discontinuous outcrops and the variable nature of the strata. As a result, radiometric ages are the best method for comparing the ages of disparate fossil localities (Trujillo, 2006).

As part of a long-term, multi-faceted study of the Morrison Formation, Kowallis and others (1998) published nine $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Morrison Formation, as well as listing older $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{40}\text{K}/^{40}\text{Ar}$ ages previously obtained from these rocks. The ages reported

*Trujillo, K.C., and Kowallis, B.J., 2015, Recalibrated legacy $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the Upper Jurassic Morrison Formation, Western Interior, U.S.A.: *Geology of the Intermountain West*, v. 2, p. 1-8.*

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in Kowallis and others (1998) were obtained from sanidine crystals collected from presumed ashfall beds. All but one age was obtained from localities on the Colorado Plateau in eastern Utah; the other age was obtained from a sample collected from south-central Colorado, near Cañon City. As these ages were the only existing radiometric ages with good resolution from the Morrison Formation, they have been used extensively in many different papers about various aspects of the formation (e.g., Turner and Peterson, 1999; Foster, 2003).

Over the last decade, researchers have been working to bring the $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{238}\text{U}/^{206}\text{Pb}$ dating systems into better agreement with one another, with inter-calibration projects adding new data to our understanding of critical times in Earth history (e.g., Sageman and others, 2014). In addition, the $^{40}\text{Ar}/^{39}\text{Ar}$ system has undergone revisions to some of its major components. The age of the Fish Canyon Tuff sanidine (FCs), one of the main fluence monitors (standards) used in $^{40}\text{Ar}/^{39}\text{Ar}$ dating, has been modified several times and discussions of its age are ongoing (e.g., Renne, 2014; Sageman and others, 2014). Initially, the FCs was proposed as a standard with an age of 27.79 Ma (millions of years before present) (Cebula and others, 1986). This age was determined relative to the age of another standard, the McClure Mountain hornblende (MMhb-1). Later, when the MMhb-1 age was revised upward, the FCs age was increased to 27.84 Ma (Samson and Alexander, 1987). This age for the FCs was used until Renne and others (1998) published an age of 28.02 Ma for this standard, which they determined by comparison with another standard known as the GA1550 biotite. Kuiper and others (2008) published a new FCs age based on inter-calibration with the astronomical time scale. This new, more precise age of 28.201 ± 0.046 Ma also utilized a new decay constant (i.e., Min and others, 2000), and researchers with the EarthTime project (an international scientific initiative supported by the National Science Foundation; www.earth-time.org) voted to adopt this value for the FCs in future publications. Renne and others (2010) then published new ^{40}K decay constants that used an approach that was independent of astronomical dating and included data from both $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{238}\text{U}/^{206}\text{Pb}$ dating. These new constants resulted in an age for the FCs of 28.305 ± 0.036 Ma (Renne and others, 2010). Not all

workers agreed with these methods and results, however, and Schwartz and others (2011) published a comment that questioned some of the methods used by Renne and others (2010). As a result, Renne and others (2011) published a reply in which they agreed with questions raised by Schwartz and others (2011) about one aspect of their methods (the use of data from liquid scintillation counting techniques), and they removed this data from their calculations. This changed their age for the FCs to 28.294 ± 0.036 Ma. Even with this change, however, some workers (e.g., Alexandre, 2011; Meyers and others, 2012) have questioned aspects of Renne and others (2010, 2011).

Most recently, Sageman and others (2014) looked at three proposed sets of ^{40}K total decay constants and associated ages for the FCs: from Renne and others (1998), from Kuiper and others (2008), and from Renne and others (2010, 2011). They took seven Cretaceous samples dated with both $^{238}\text{U}/^{206}\text{Pb}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ methods, and calculated new $^{40}\text{Ar}/^{39}\text{Ar}$ ages using the three different sets of decay constants and FCs ages. They concluded that in all seven pairs, using the FCs age of 28.201 ± 0.046 Ma of Kuiper and others (2008) gave the best agreement with the $^{238}\text{U}/^{206}\text{Pb}$ ages.

Currently, the majority of $^{40}\text{Ar}/^{39}\text{Ar}$ researchers have adopted the astronomically calibrated age of the FCs of 28.201 ± 0.046 Ma from Kuiper and others (2008), as well as Min and others (2000) ^{40}K decay constant of $5.463 \pm 0.107 \times 10^{-10}$ (Sageman and others, 2014).

These new developments in $^{40}\text{Ar}/^{39}\text{Ar}$ dating methodology have led to the need to recalibrate the older, “legacy” ages for various samples dated by $^{40}\text{Ar}/^{39}\text{Ar}$ methods. Recalibrated ages for samples from the Morrison Formation are reported here (figure 1; table 1), and it is our hope that researchers will use these ages in lieu of the previously published ages when referring to the age of the Morrison Formation.

METHODS

Data from the original $^{40}\text{Ar}/^{39}\text{Ar}$ dating process (Kowallis and others, 1998) was entered into a recalibration calculation spreadsheet created by N. McLean (University of Kansas) and available on the EarthTime website (www.earth-time.org). The decay constants, fluence monitor ages, and uncertainties used in the cal-

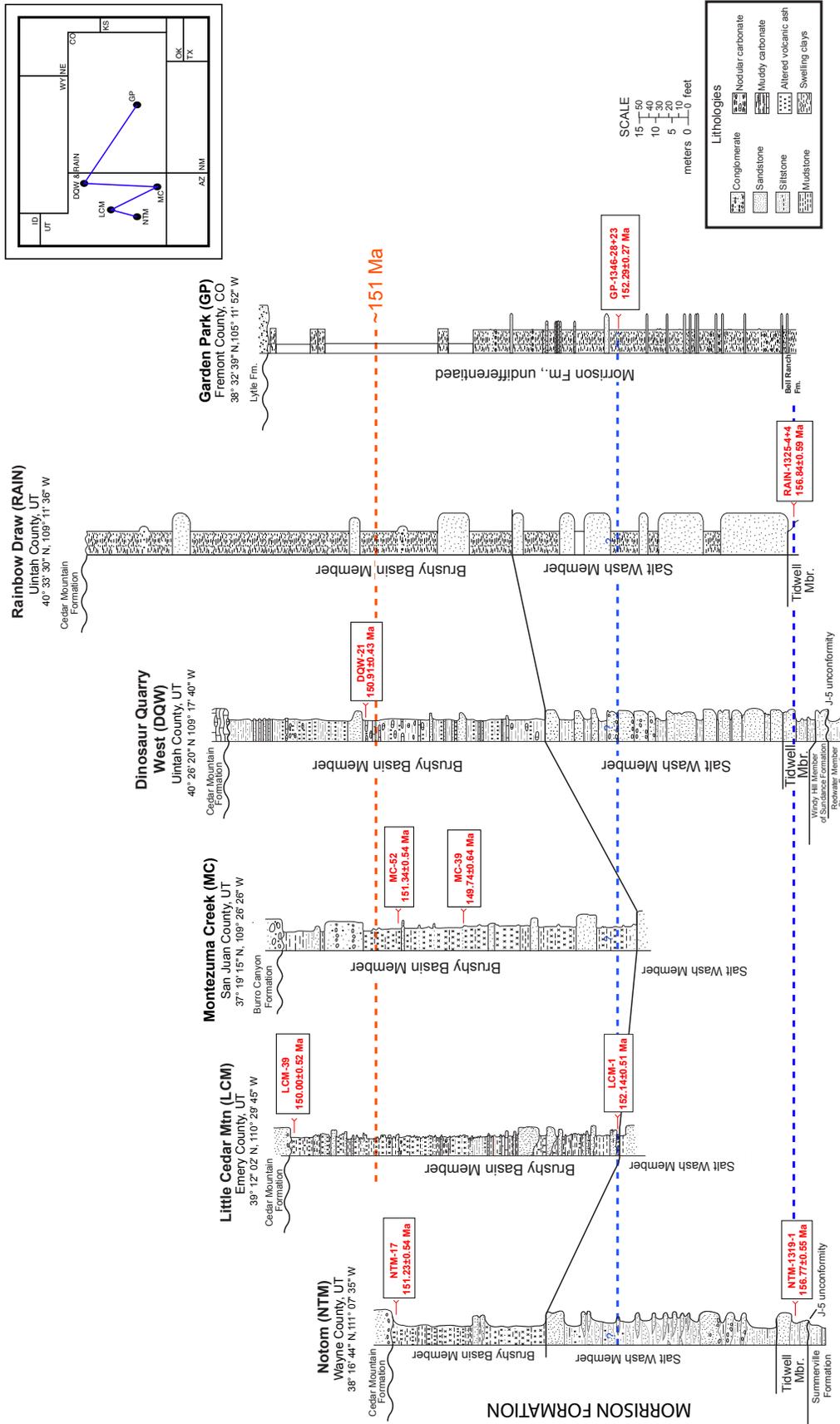


Figure 1. Recalibrated ⁴⁰Ar/³⁹Ar ages from the Morrison Formation, placed onto local stratigraphic sections where samples were collected. Stratigraphic sections loosely correlated based on ⁴⁰Ar/³⁹Ar ages that are within analytical error of each other (blue dashed lines). Orange dashed line shows an estimate of the placement of 151 Ma timeline based on stratigraphic positions of ⁴⁰Ar/³⁹Ar ages. Sample areas shown on inset map. Notom section from Kowallis and Heaton (1987); Little Cedar Mtn., Dinosaur Quarry West, and Montezuma Creek sections measured by C.E. Turner and F. Peterson, U.S. Geological Survey, written communication (1988); Rainbow Draw section from Turner and Peterson (1999); Garden Park section measured by F. Peterson, U.S. Geological Survey, written communication (1991).

culations are listed in table 2, as are the legacy age data used such as the J value (a parameter associated with the irradiation of ^{39}K to create ^{39}Ar) for each sample and their uncertainties.

It should be noted that although we chose the age for the FCs of 28.201 ± 0.046 Ma from Kuiper and others (2008) and the ^{40}K decay constant of $5.463 \pm 0.107 \times 10^{-10}$ from Min and others (2000) as discussed above, because of ongoing discussions and research on these topics other workers may chose to use different values (e.g., Irmis and others, 2013). The practical differences in the recalibrated ages are small (0.03% in the case of Irmis and others, 2013), however, regardless of which values are used.

DISCUSSION

The recalibrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages for nine samples from the Morrison Formation reported here (figure 1; table 1) are useful for researchers looking to place better age constraints on the flora and fauna of the Morrison

Formation, as well as for those working to understand the stratigraphic relationships across the formation. They are also now more useful for comparisons with newer $^{238}\text{U}/^{206}\text{Pb}$ ages that have recently been published (Kowallis and others, 2007; Bradshaw and Kowallis, 2009; Trujillo and others, 2006, 2008, 2014; Trujillo and Chamberlain, 2013).

It should be noted, however, that comparing ages obtained by $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{238}\text{U}/^{206}\text{Pb}$ methods is not simply a case of looking at the numbers. Two potential issues regarding the uncertainties in ages must be addressed. First, there are differences in the ways that uncertainties are reported between the $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{238}\text{U}/^{206}\text{Pb}$ systems. With $^{40}\text{Ar}/^{39}\text{Ar}$ ages, the convention is to report the uncertainty in the ages as 1-sigma, while $^{238}\text{U}/^{206}\text{Pb}$ ages are almost always reported with 2-sigma uncertainties. Workers should be aware of this difference, as it may result in misunderstood comparisons between ages obtained with the two different systems.

Second, although recalibrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages are

Table 1. Recalibrated ages in Ma for samples from the Upper Jurassic Morrison Formation, dated by single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ laser fusion methods. Geographic and stratigraphic information from Kowallis and others (1998). See table 2 for details on recalibrations. All samples processed at the Berkeley Geochronological Center.

Sample name	Published age (1 σ error with error in J)	Recalibrated age	converted age uncertainties			Strat. level of sample	Sample area	County	State	Location of top of section	
			internal 1 σ	internal + std	internal + std + λ					Lat.	Long.
LCM-39	148.07 \pm 0.51	150.00	\pm 0.52	\pm 0.53	\pm 2.99	104.5 m above base of Brushy Basin Mbr.	Little Cedar Mtn	Emery	UT	39°12'02"N	110°29'45"W
DQW-21	148.97 \pm 0.42	150.91	\pm 0.43	\pm 0.44	\pm 2.99	55.4 m above base of Brushy Basin Mbr.	Dinosaur Quarry West/Douglass Draw	Uintah	UT	40°26'20"N	109°17'40"W
MC-52	149.39 \pm 0.53	151.34	\pm 0.54	\pm 0.55	\pm 3.01	63.5 m above base of Brushy Basin Mbr.	Montezuma Creek	San Juan	UT	37°19'15"N	109°26'26"W
NTM-17	149.29 \pm 0.52	151.23	\pm 0.54	\pm 0.54	\pm 3.01	48.5 m above base of Brushy Basin Mbr.	Notom	Wayne	UT	38°16'44"N	111°07'35"W
MC-39	147.82 \pm 0.63	149.74	\pm 0.64	\pm 0.65	\pm 3.00	51 m above base of Brushy Basin Mbr.	Montezuma Creek	San Juan	UT	37°19'15"N	109°26'26"W
LCM-1	150.18 \pm 0.5	152.14	\pm 0.51	\pm 0.52	\pm 3.02	3.8 m above base of Brushy Basin Mbr.	Little Cedar Mtn	Emery	UT	39°12'02"N	110°29'45"W
GP-1346-28+23	150.33 \pm 0.27	152.29	\pm 0.27	\pm 0.30	\pm 3.00	56 m above base of fm.	Garden Park	Fremont	CO	38°32'39"N	105°11'52"W
NTM-1319-1	154.75 \pm 0.54	156.77	\pm 0.55	\pm 0.56	\pm 3.12	2.4 m above base of Tidwell Mbr.	Notom	Wayne	UT	38°16' 44"N	111°07'35"W
RAIN-1325-4+4	154.82 \pm 0.58	156.84	\pm 0.59	\pm 0.60	\pm 3.13	2.7 m above base of fm.	Rainbow Draw	Uintah	UT	40°33'30"N	109°11'36"W

now in much better agreement with $^{238}\text{U}/^{206}\text{Pb}$ ages overall, attention needs to be paid to the uncertainties propagated by recalibration when comparing ages obtained by the different methods. For this study, in tables 1 and 2 the first uncertainty given (converted age uncertainties, internal 1σ column) is the uncertainty involved in the analysis itself. This is the uncertainty that should be used when comparing recalibrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained by the same lab (Berkeley Geochronological Center) using the same methods, standards, and decay constants. In the data reported here, this is the uncertainty that should be used when only these reported recalibrated ages are of interest.

The second uncertainty given in tables 1 and 2 (converted age uncertainties, internal + standard column) includes the analytical uncertainty as well as the uncertainty in the age of the fluence monitor (standard, the Fish Canyon Tuff sanidine in this case). This is the uncertainty that should be used when comparing recalibrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages from different labs or when different fluence monitors are used.

The final, largest uncertainty given in tables 1 and 2 (converted age uncertainties, internal + standard + λ column) includes the analytical uncertainty, the uncertainty in the age of the fluence monitor, and the un-

certainty in the decay constant. This is the uncertainty that should be used when comparing ages obtained by $^{40}\text{Ar}/^{39}\text{Ar}$ methods with those obtained by $^{238}\text{U}/^{206}\text{Pb}$ methods.

The size of this largest uncertainty is disconcerting, as with a range of approximately 6 million years it spans much of the understood depositional time of the entire Morrison Formation. As a result, it would seem that using the new recalibrated legacy $^{40}\text{Ar}/^{39}\text{Ar}$ ages along with new $^{238}\text{U}/^{206}\text{Pb}$ ages obtained for the Morrison Formation could be fraught with error.

The importance of this uncertainty to the practical use of these ages is unclear at present. Without more data, it is difficult to make this determination; however, two of the localities where legacy $^{40}\text{Ar}/^{39}\text{Ar}$ ages were obtained from the Morrison Formation at Notom, Utah, have also been dated using $^{238}\text{U}/^{206}\text{Pb}$ methods (Kowallis and others, 2007; Bradshaw and Kowallis, 2010). If we look at the recalibrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages without taking the uncertainties into account, they are in very close agreement with the $^{238}\text{U}/^{206}\text{Pb}$ ages for these same localities (figure 2). These preliminary data suggest that although the uncertainties are large when comparing ages obtained by the two different dating systems, the data themselves may still be useful.

Table 2. Data and calculations used for recalibrations of legacy $^{40}\text{Ar}/^{39}\text{Ar}$ data from the Upper Jurassic Morrison Formation. Sample data from Kowallis and others (1995, 1998). Results calculated using spreadsheet developed by N. McLean (University of Kansas), available at www.earth-time.org.

INPUT FOR ALL SAMPLES									
Decay constant and standard age used for legacy data:									
λ old	5.543E-10	/yr		(λ = Decay constant, from Steiger and Jäger, 1977)					
age of standard, old	27.84	Ma		(age of Fish Canyon Tuff sanidine standard from Renne and others, 1998)					
Decay constant and standard age used for conversion:									
λ new	5.463E-10	± 1.07E-11	/yr, 1σ	(λ = Decay constant, from Min and others, 2000)					
age of standard, new	28.201	± 0.023	Ma, 1σ	(age of Fish Canyon Tuff sanidine standard from Kuiper and others, 2008)					
Sample Name (in stratigraphic order)	INPUT			Input for Error Propagation:			Output (all 1σ absolute)		
	legacy data age:		converted age:	legacy data age		legacy data J	converted age uncertainties:		
	sample age, old (Ma)	sample age, new (Ma)	Relative Change	1σ internal	J value	J 1σ unct.	internal	internal + standard	internal + standard + λ
LCM-39	148.07	150.00	1.29%	± 0.51	0.03801	± 0.00013	± 0.52	± 0.53	± 2.99
DQW-21	148.97	150.91	1.29%	± 0.42	0.01067	± 0.00003	± 0.43	± 0.44	± 2.99
MC-52	149.39	151.34	1.29%	± 0.53	0.03832	± 0.00013	± 0.54	± 0.55	± 3.01
NTM-17	149.29	151.23	1.29%	± 0.52	0.03824	± 0.00013	± 0.53	± 0.54	± 3.01
MC-39	147.82	149.74	1.29%	± 0.63	0.03823	± 0.00013	± 0.64	± 0.65	± 3.00
LCM-1	150.18	152.14	1.29%	± 0.5	0.03816	± 0.00013	± 0.51	± 0.52	± 3.02
GP-1346-28+23	150.33	152.29	1.29%	± 0.27	0.01674	± 0.00001	± 0.27	± 0.30	± 3.00
NTM-1319-1	154.75	156.77	1.29%	± 0.54	0.03793	± 0.00013	± 0.55	± 0.56	± 3.12
RAIN-1325-4+4	154.82	156.84	1.29%	± 0.58	0.03811	± 0.00013	± 0.59	± 0.60	± 3.13

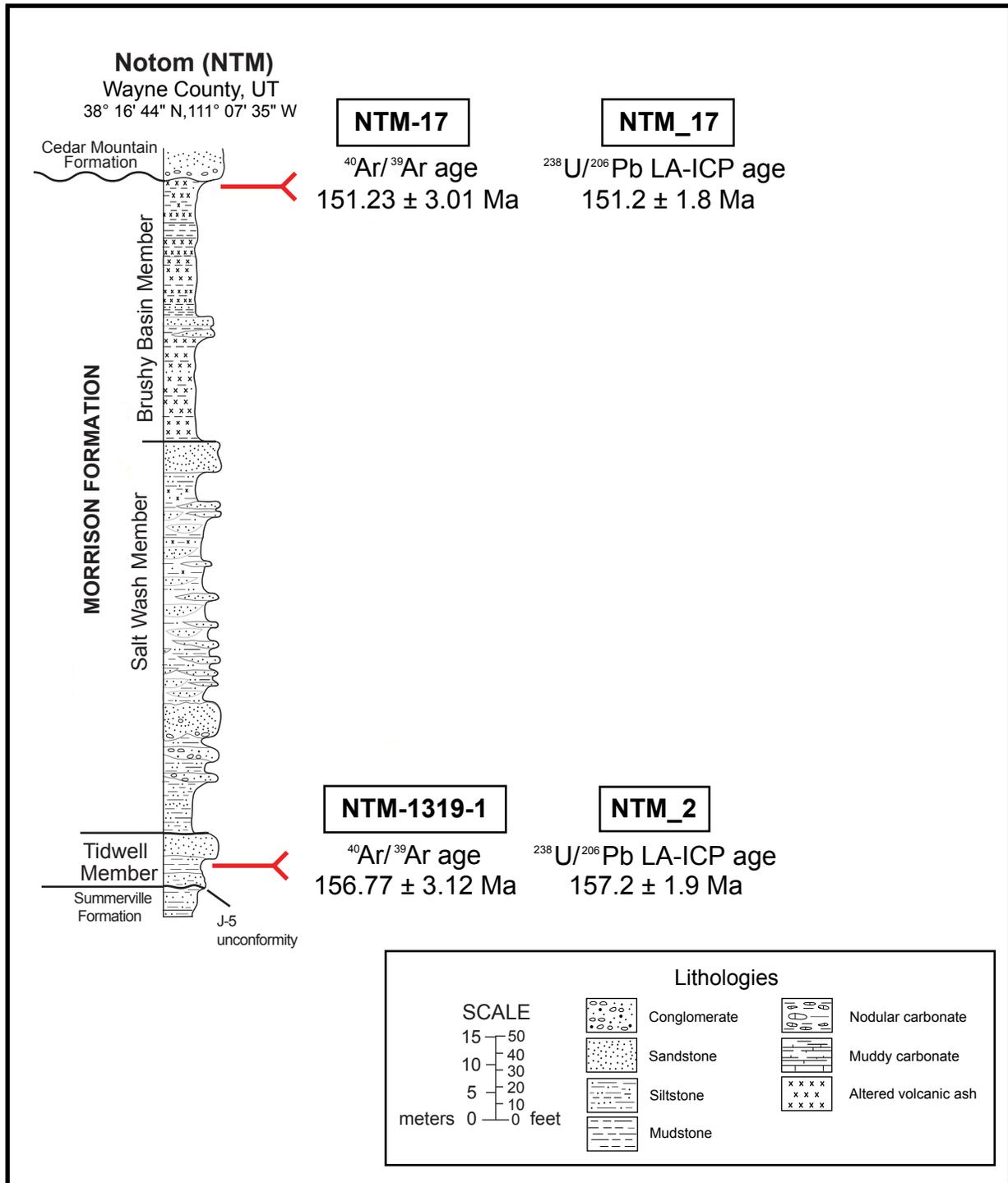


Figure 2. Comparison of $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{238}\text{U}/^{206}\text{Pb}$ ages on samples from the same localities at Notom, Utah. $^{40}\text{Ar}/^{39}\text{Ar}$ ages shown with analytical uncertainty, uncertainty in fluence monitor, and uncertainty in decay constant included. See figure 1 for location of section. Section from Kowallis and Heaton (1987).

SUMMARY

The recalibration of these legacy $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Upper Jurassic Morrison Formation adds new use-

ful data for researchers interested in this widespread rock unit. Along with these ages, additional radiometric ages from other geographic areas across the depositional area of the formation will help in decoding the tem-

poral relationships among the floras and faunas. Techniques for isolating and analyzing very small crystals continue to improve, and more radiometric ages from the Morrison Formation are forthcoming. In addition, dating of more samples by both $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{238}\text{U}/^{206}\text{Pb}$ methods would help in determining how much emphasis to place on the high uncertainties when comparing ages obtained by the two dating methods.

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