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Short Communication

Data reporting norms for ^{40}Ar/^{39}Ar geochronology

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ABSTRACT

Data reported in ^{40}Ar/^{39}Ar geochronology studies are commonly insufficient to allow computation of ages. This deficiency renders it difficult to compare ages based on different standards or constants, and often hinders critical evaluation of the results. Herein are presented an enumeration of the data that should be reported in all ^{40}Ar/^{39}Ar studies, including a discussion in support of these requirements. The minimum required data are identified and distinguished from parameters that are useful but may be derived from them by calculation. Finally, recommendations are made for metadata needed to document age calculations (e.g., from age spectrum or isochron analyses).

1. Introduction

As with other geochemical data, it is increasingly evident that there is a need for minimal norms for reporting ^{40}Ar/^{39}Ar geochronological results. This issue was broadly addressed by Goldstein et al. (2003) for some types of isotope data published in *Chemical Geology*, but the ^{40}Ar/^{39}Ar system was not explicitly included in that discussion. The ^{40}Ar/^{39}Ar radioisotope system is somewhat unique and sufficiently important in the Earth and planetary sciences to warrant special attention. The overarching goal is to consistently provide journal readers with all the information needed to perform independent analysis of ^{40}Ar/^{39}Ar data, using readily available freeware (e.g., Koppers, 2002), requiring them to make as few assumptions as possible about how the original authors computed ages or ancillary information. In some cases this will allow conclusions that may depart from those of the data-originator, which is useful in promoting scientific vitality.

Implementation of these norms will facilitate straightforward recalculation of ages based on updated information such as decay constants, data for standards, interference corrections, or isotopic abundances. Adoption of these norms will also facilitate incorporation of ^{40}Ar/^{39}Ar data into databases such as GEOCHRON (www.earthchem.org/GEOCHRON), which are becoming increasingly numerous and important as research and pedagogical tools. Establishing specific norms will also facilitate editorial handling of manuscripts by providing journal editors or their designees, who

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are often non-specialists, with explicit community-endorsed data reporting criteria rather than forcing them to rely solely on the vagaries of peer review.

Process automation and the motivation for increased accuracy and precision have launched a trend towards more voluminous data produced in typical ^{40}Ar/^{39}Ar studies. It may thus appear onerous, in light of bourgeoning data proliferation, to require a more complete reporting of data than is presently the norm. However, the increasing use of internet-based data archives by many journals is rendering obsolete the limitations of precious printed journal space. In order to maximize the utility of data to the broadest possible audience, it is critical to make all necessary data readily available. In this short communication we discuss the minimum information that should be reported, and the rationale for these selections. The norms discussed here are specific to terrestrial materials, as additional information (e.g., for solar wind and cosmogenic isotopes) is generally required for extraterrestrial samples.

2. General considerations

2.1. Sample number, type, location, petrology, and context

A unique identifier such as an International Geo Sample Number (IGSN) is recommended to facilitate inclusion in databases (see http://www.geosamples.org/). The rock type from which the sample is prepared should be described using standard terminology. Further details, such as mineral chemistry or structure, may be relevant and in such cases should be presented, but the nature of such data is highly case-specific and its specification is beyond the scope of the present recommendations. To facilitate geological interpretation of data, it is essential to specify at a minimum the map coordinates (e.g., latitude and longitude) of samples, including grid and datum. With modern GPS capabilities it should be possible to specify sample locations with better than a few tens of meters accuracy. For chronostratigraphic studies it is critical to indicate stratigraphic position information as well, and depths should be reported for borehole and submarine samples.

2.2. Sample treatment

The material analyzed should always be specified, as well as its configuration (e.g., single crystals versus multigrain aliquots, groundmass versus whole-rock, etc.) and grain size or mass should be given. Mineral separation techniques such as use of heavy liquids (specify type) and magnetic separators should be mentioned. Acids used should be specified by composition, concentration, and duration.

2.3. Uncertainties

A fundamental point is that uncertainties in all parameters should be stated at the 1σ level as this is the fundamental, formula-driven statistic. Optionally, relative errors or coefficients of variation can be provided as these are especially useful for comparisons and to facilitate error propagation. For comparison with other data it may be useful to state computed ages with 2σ errors or 95% confidence intervals *in addition* (i.e., not to replace the 1σ norm) – it is recommended to confine such usage to text or summary tables with clear designation.

2.4. Significant figures

A common obstacle to recalculating ages or ancillary data such as chemical signatures accurately is that sufficient significant figures are often not reported, resulting in rounding errors. This point is stressed emphatically. Uncertainties, or even isotope concentrations, that read zero solely due to rounding must in any case be avoided, by showing results with sufficient significant digits. This is especially problematic for ^{36}Ar, whose impact on the age equation is magnified by a factor of $\sim$300 in the air correction. For guidelines on significant figures of both values and their uncertainties, see e.g., Taylor (1982).

2.5. Time units

In keeping with *Quaternary Geochronology* editorial policy (Grün, 2008), the units of time are ka, Ma, and Ga. There is no distinct unit for time differences.

3. Minimum data

The minimum data that should be provided are those necessary to reproduce the ages inferred for samples or subsamples (i.e., step ages in step-heating analyses). This includes measured relative isotopic abundances for samples and standards, and summaries of data obtained for backgrounds and air pipettes (or whatever basis is used to determine sensitivity and mass discrimination). Values not heretofore reported in typical studies, but still needed to calculate ages, must also be specified along with their uncertainties. These include age of the standard(s), atmospheric argon isotope ratios, interfering isotope production ratios, and decay constants.

3.1. Relative isotope abundances

A cornerstone of the minimum data required is the relative abundances of argon isotopes and their uncertainties for ^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, and ^{36}Ar. The term *relative* isotope abundances means that the value given for each isotope is relative to the values of all others, and these do not in and of themselves reveal absolute abundances. These quantities should be corrected for background (blank), mass discrimination, and radioactive decay. Although ^{38}Ar does not enter into the age equation explicitly, it is a useful geochemical proxy for Cl and can be critical for evaluating the production of interfering isotopes in the reactor, i.e., ^{36}Ar from Cl (e.g., Renne et al., 2008). Similarly, ^{37}Ar may be unimportant to the age calculation for Ca-poor samples, but its value is nonetheless useful for evaluating reactor processes and sample composition. The relative abundances of each isotope should be given for each individual measurement, in case a stepwise heating experiment or repeated analyses of the same sample material are reported. These values (and their units, e.g., nA or mV of amplified beam current or voltage, or counts per second of ion flux) and the value (in ohms) of any resistor(s) used should be given, rather than isotope ratios (e.g., ^{36}Ar/^{39}Ar, ^{37}Ar/^{39}Ar, ^{38}Ar/^{39}Ar, and ^{40}Ar/^{39}Ar as commonly reported) because it is more cumbersome to calculate uncertainties for derived isotope ratios (i.e., as required for isochron analysis) using the latter. For example, for an isochron one must calculate ^{40}Ar/^{36}Ar or ^{36}Ar/^{40}Ar. If this ratio is computed from ^{36}Ar/^{39}Ar and ^{40}Ar/^{39}Ar values without additional information about error correlation, the uncertainty in ^{36}Ar/^{40}Ar will implicitly contain a contribution from the uncertainty in ^{39}Ar measurement, which is irrelevant and in fact will produce spuriously large uncertainties (and spuriously low MSWD values). Reporting relative abundances rather than ratios also facilitates the computation of error correlations, as needed e.g., for isochron regressions (e.g., Ludwig and Titterington, 1994).

Table 1
Ar/Ar data and constants used in age calculations. All errors shown at 1σ. Columns in grey are optional but recommended.

Sample: SH-10	Lab #: 33018-23	J: 0.026703 ± 0.000035	D^1: 1.0066 ± 0.0028	Heating: 60 s
Plagioclase	IGSN #: PRR001S35			

Irradiation coordinates: $x = 0.53$ cm; $y = 0.85$ cm; $z = 0.31$ cm

N	Power (W)	^{40}Ar (moles)	^{40}Ar (10^{-9} A)	$\pm\sigma_{40}$ (10^{-12} A)	^{39}Ar (10^{-10} A)	$\pm\sigma_{39}$ (10^{-13} A)	^{38}Ar (10^{-12} A)	$\pm\sigma_{38}$ (10^{-14} A)	^{37}Ar (10^{-9} A)	$\pm\sigma_{37}$ (10^{-12} A)	^{36}Ar (10^{-13} A)	$\pm\sigma_{36}$ (10^{-14} A)	%^{40}Ar*	^{40}Ar*/^{39}Ar$_K$
A	0.5	1.02E−15	0.09713	0.43	0.13065	0.75	0.1826	1.40	0.00623	0.34	0.894	1.58	73.3	5.44705
B	1.0	2.97E−15	0.28389	0.59	0.37977	1.03	0.5222	1.56	0.04644	0.41	2.958	1.66	70.5	5.26945
C	2.0	4.83E−15	0.46124	0.68	0.80945	1.82	1.1409	1.91	0.30175	1.25	3.437	1.74	83.2	4.74526
D	3.0	9.57E−15	0.91352	0.86	1.67572	2.51	2.0841	2.12	0.86354	1.74	3.155	1.62	97.3	5.31674
E	3.5	8.23E−15	0.78615	1.11	1.42415	1.92	1.7982	1.93	0.79177	2.18	2.493	1.70	98.7	5.45845
F	4.0	1.08E−14	1.03031	0.99	1.84797	1.42	2.3459	2.22	1.04196	4.53	3.466	1.78	98.1	5.48319
G	4.5	1.58E−14	1.50503	1.91	2.68337	2.31	3.2651	2.45	1.43274	5.81	4.354	1.63	99.1	5.56719
H	5.0	1.23E−14	1.17480	0.72	2.10604	1.92	2.6711	2.45	1.18087	2.37	3.220	1.71	99.9	5.58655
I	5.5	1.07E−14	1.02511	1.21	1.82579	1.42	2.1541	2.54	1.06036	3.82	3.095	1.88	99.3	5.59020
J	6.0	9.84E−15	0.93946	0.97	1.66172	1.72	2.0981	2.51	0.90347	2.01	2.904	1.66	98.6	5.58306
K	7.0	1.49E−14	1.42628	1.01	2.52346	2.22	3.1186	2.79	1.33248	2.55	4.526	1.74	98.1	5.55503
L	8.0	1.10E−14	1.04627	1.21	1.86079	1.72	2.3874	2.15	1.14403	4.55	3.554	1.74	98.7	5.56264
M	9.0	1.05E−14	1.00506	1.31	1.79407	2.31	2.1591	2.49	1.02569	2.55	2.837	1.19	99.8	5.60404
N	10.0	6.41E−15	0.61219	1.01	1.09883	2.02	1.2350	2.22	0.64627	1.43	1.781	1.16	99.8	5.57491
O	11.0	5.73E−15	0.54674	0.40	0.98238	1.82	1.1939	1.87	0.64561	3.47	1.745	1.13	100.0	5.57995
P	13.0	1.18E−14	1.13165	1.10	2.03544	2.02	2.4908	2.57	1.26407	2.56	3.588	1.60	99.6	5.54828
Q	15.0	1.32E−14	1.25708	1.30	2.23161	2.32	2.7392	2.38	1.31670	5.11	4.075	1.77	98.8	5.57751
R	17.0	6.91E−15	0.65976	0.96	1.17350	2.12	1.4085	2.20	0.70525	1.58	2.325	1.60	98.1	5.52946
S	19.0	5.45E−15	0.52065	0.89	0.93267	1.72	1.1549	1.94	0.56381	1.28	1.599	1.52	99.6	5.57175
T	21.0	2.29E−15	0.21907	0.64	0.39150	1.23	0.4764	1.70	0.29765	1.25	0.818	1.60	99.8	5.60246
U	25.0	2.61E−15	0.24968	0.65	0.43979	1.13	0.5508	1.86	0.31461	1.20	0.895	1.45	99.5	5.66349
V	30.0	2.07E−15	0.19761	0.57	0.35355	1.13	0.4359	1.61	0.20480	0.95	0.745	1.51	97.1	5.44124
W	35.0	1.52E−15	0.14560	0.39	0.25177	0.87	0.2547	1.35	0.15352	0.77	0.719	1.43	93.8	5.43822
X	40.0	9.78E−16	0.09338	0.31	0.07986	0.67	0.0948	1.35	0.04472	0.47	2.090	1.68	37.6	4.40197

Plateau Age (steps E–X):

Standard: FCs	Lab #: 33019	Age: 28.02 Ma	D^1: 1.0064 ± 0.0025	Heating: 11s

Irradiation coordinates: $x = 0.53$ cm; $y = 0.85$ cm; $z = 0.31$ cm

N	Power (W)	^{40}Ar (moles)	^{40}Ar (10^{-9} A)	$\pm\sigma$ (10^{-12} A)	^{39}Ar (10^{-8} A)	$\pm\sigma$ (10^{-12} A)	^{38}Ar (10^{-10} A)	$\pm\sigma$ (10^{-13} A)	^{37}Ar (10^{-10} A)	$\pm\sigma$ (10^{-13} A)	^{36}Ar (10^{-13} A)	$\pm\sigma$ (10^{-14} A)	%^{40}Ar*	^{40}Ar*/^{39}Ar$_K$
1	6	1.50E−13	14.24722	5.41	2.40864	8.1	2.90784	3.40	1.7624	3.6	2.93	3.83	99.5	0.587201
2	6	9.32E−14	8.83707	4.81	1.49479	6.3	1.79535	2.30	0.9241	3.6	0.88	3.18	99.8	0.588753
3	6	6.89E−14	6.53115	4.31	1.10531	6.0	1.34318	3.40	0.9526	6.0	1.78	3.64	99.3	0.585437
4	6	2.78E−13	26.31198	11.00	4.48005	16.0	5.39509	5.30	3.1305	6.0	2.57	3.70	99.8	0.584912
5	6	8.86E−14	8.39561	5.80	1.41043	6.7	1.69933	1.90	1.0669	3.3	4.91	3.51	98.4	0.584240

Weighted Mean J:

Explanations
D^1: Mass discrimination per AMU based on power law
Δt^2: Time interval (days) between end of irradiation and beginning of analysis
Blank Type^3: Ave = average; LR = linear regression versus time

Constants used		Source
Atmospheric argon ratios		
$(^{40}\text{Ar}/^{36}\text{Ar})_A$	296.0 ± 0.74	Nier (1950)
$(^{40}\text{Ar}/^{38}\text{Ar})_A$	0.1880 ± 0.0001	Nier (1950)
Interfering isotope production ratios		
$(^{40}\text{Ar}/^{39}\text{Ar})_K$	(7.30 ± 0.92)E−04’	Renne et al. (2005)
$(^{38}\text{Ar}/^{39}\text{Ar})_K$	(1.22 ± 0.00)E−02	Renne et al. (2005)
$(^{37}\text{Ar}/^{39}\text{Ar})_K$	(2.24 ± 0.16)E−04	Renne et al. (2005)
$(^{39}\text{Ar}/^{37}\text{Ar})_{Ca}$	(6.95 ± 0.09)E−04	Renne et al. (2005)
$(^{38}\text{Ar}/^{37}\text{Ar})_{Ca}$	(1.96 ± 0.08)E−05	Renne et al. (2005)
$(^{36}\text{Ar}/^{37}\text{Ar})_{Ca}$	(2.65 ± 0.02)E−04	Renne et al. (2005)
$(^{36}\text{Cl}/^{38}\text{Cl})_{Cl}$	263 ± 2	Renne et al. (2008)
Decay constants		
^{40}K λ_ϵ	(5.81 ± 0.00)E−11 a^{-1}	Steiger and Jäger (1977)
^{40}K λ_β	(4.962 ± 0.000)E−10 a^{-1}	Steiger and Jäger (1977)
^{39}Ar	(2.58 ± 0.03)E−03 a^{-1}	Stoenner et al. (1965)
^{37}Ar	(5.4300 ± 0.0063)E−02 a^{-1}	Renne and Norman (2001)
^{36}Cl λ_β	(2.35 ± 0.02)E−06 a^{-1}	Endt (1998)

3.2. First-order corrections

The relative isotope abundance data should be corrected for baseline, background, mass discrimination and/or detector intercalibration, and radioactive decay, and the basis for these corrections should be specified. The relative isotope abundances reported in fundamental data tables should not be corrected for any nuclear interfering reactions, whereas they must be applied to

Heating: 60 s
IGSN #: PRR001S35

Irradiation coordinates: $x = 0.53$ cm; $y = 0.85$ cm; $z = 0.31$ cm

Background Correction

$\pm\sigma$	Age (Ma)	$\pm\sigma$ (Ma)	Ca/K	Δt^2 (days)	Blank type[3]	^{40}Ar (10^{-12} A)	$\pm\sigma_{40}$ (10^{-14} A)	^{39}Ar (10^{-14} A)	$\pm\sigma_{39}$ (10^{-15} A)	^{38}Ar (10^{-15} A)	$\pm\sigma_{38}$ (10^{-16} A)	^{37}Ar (10^{-15} A)	$\pm\sigma_{37}$ (10^{-16} A)	^{36}Ar (10^{-15} A)	$\pm\sigma_{36}$ (10^{-16} A)
0.33890	244.99	15.24	0.94	146.50	LR	3.81130	1.906	1.511	1.21	1.82	1.6	4.30	0.8	3.70	0.6
0.12829	237.51	5.78	2.40	146.52	LR	3.81062	1.905	1.511	1.21	1.82	1.6	4.30	0.8	3.70	0.6
0.06661	215.23	3.02	7.31	146.55	LR	3.80924	1.905	1.510	1.21	1.81	1.6	4.30	0.8	3.70	0.6
0.03604	239.50	1.62	10.10	146.60	LR	3.80649	1.903	1.509	1.21	1.81	1.6	4.29	0.8	3.70	0.6
0.04152	245.47	1.87	10.90	146.63	LR	3.80302	1.902	1.508	1.21	1.81	1.6	4.29	0.8	3.69	0.6
0.03607	246.51	1.62	11.05	146.66	LR	3.79885	1.899	1.506	1.20	1.81	1.6	4.29	0.8	3.69	0.6
0.02921	250.04	1.31	10.47	146.71	LR	3.79333	1.897	1.504	1.20	1.81	1.6	4.28	0.8	3.68	0.6
0.03244	250.85	1.46	10.99	146.74	LR	3.78713	1.894	1.501	1.20	1.80	1.6	4.27	0.8	3.68	0.6
0.03766	251.00	1.69	11.38	146.76	LR	3.78026	1.890	1.499	1.20	1.80	1.6	4.26	0.8	3.67	0.6
0.03672	250.70	1.65	10.66	146.82	LR	3.77205	1.886	1.495	1.20	1.80	1.6	4.26	0.8	3.66	0.5
0.03023	249.53	1.36	10.35	146.84	LR	3.76316	1.882	1.492	1.19	1.79	1.6	4.25	0.8	3.65	0.5
0.03646	249.85	1.64	12.05	146.87	LR	3.75360	1.877	1.488	1.19	1.79	1.6	4.23	0.8	3.64	0.5
0.03102	251.58	1.39	11.21	146.92	LR	3.74277	1.871	1.484	1.19	1.78	1.6	4.22	0.8	3.63	0.5
0.03965	250.36	1.78	11.53	146.95	LR	3.73127	1.866	1.479	1.18	1.78	1.6	4.21	0.8	3.62	0.5
0.04189	250.57	1.88	12.88	146.98	LR	3.71910	1.860	1.474	1.18	1.77	1.6	4.20	0.8	3.61	0.5
0.03334	249.25	1.50	12.17	147.03	LR	3.70566	1.853	1.469	1.18	1.77	1.6	4.18	0.8	3.60	0.5
0.03334	250.47	1.50	11.56	147.06	LR	3.69160	1.846	1.463	1.17	1.76	1.6	4.16	0.8	3.58	0.5
0.04655	248.46	2.09	11.78	147.08	LR	3.67693	1.838	1.458	1.17	1.75	1.6	4.15	0.8	3.57	0.5
0.05278	250.23	2.37	11.85	147.13	LR	3.66101	1.831	1.451	1.16	1.74	1.6	4.13	0.8	3.55	0.5
0.11888	251.52	5.34	14.90	147.16	LR	3.64448	1.822	1.445	1.16	1.74	1.6	4.11	0.8	3.54	0.5
0.09719	254.07	4.36	14.02	147.19	LR	3.62735	1.814	1.438	1.15	1.73	1.6	4.09	0.8	3.52	0.5
0.12304	244.75	5.53	11.35	147.24	LR	3.60903	1.805	1.431	1.14	1.72	1.5	4.07	0.8	3.50	0.5
0.16149	244.62	7.26	11.95	147.27	LR	3.59014	1.795	1.423	1.14	1.71	1.5	4.05	0.8	3.49	0.5
0.60000	200.50	27.33	10.98	147.29	LR	3.57072	1.785	1.416	1.13	1.70	1.5	4.03	0.8	3.47	0.5
	249.78	**0.49**													

Background Correction

$\pm\sigma$	J	$\pm\sigma$	Ca/K	Δt^2 (days)	Blank type[3]	^{40}Ar (10^{-12} A)	$\pm\sigma$ (10^{-14} A)	^{39}Ar (10^{-13} A)	$\pm\sigma$ (10^{-15} A)	^{38}Ar (10^{-15} A)	$\pm\sigma$ (10^{-16} A)	^{37}Ar (10^{-15} A)	$\pm\sigma$ (10^{-16} A)	^{36}Ar (10^{-15} A)	$\pm\sigma$ (10^{-16} A)
0.001619	0.026657	0.000073	0.014	70.05	Ave	7.59623	3.136	5.4374	4.38	2.90784	3.40	3.71	0.5	5.07	0.7
0.001683	0.026586	0.000076	0.012	70.08	Ave	7.59623	3.136	5.4374	4.38	1.79535	3.40	3.71	0.5	5.07	0.7
0.001880	0.026737	0.000086	0.017	70.10	Ave	7.59623	3.136	5.4374	4.38	1.34318	3.40	3.71	0.5	5.07	0.7
0.001550	0.026761	0.000071	0.014	70.16	Ave	7.59623	3.136	5.4374	4.38	5.39509	3.40	3.71	0.5	5.07	0.7
0.001812	0.026792	0.000083	0.015	70.18	Ave	7.59623	3.136	5.4374	4.38	1.69933	3.40	3.71	0.5	5.07	0.7
	0.026703	**0.000035**													

determine the optional parameters %^{40}Ar* and ^{40}Ar*/^{39}Ar$_K$. It is generally impractical to report all of the raw measurements used for background (blank) correction, but it is practical to report the computed background values used to correct each isotope for each measurement, and this is encouraged to facilitate evaluation of results' robustness (e.g., backgrounds' contribution to the overall age uncertainty). It must be stated whether the correction is based on average values, regression versus time, etc. For mass discrimination correction the basis includes the number of air aliquots (or other isotope ratio standard) measured and their temporal relationship to the sample analyses. The reference value(s), e.g., Nier (1950), Steiger and Jäger (1977)[1], Lee et al. (2006) must be specified. It is also important to state the assumed form of the relationship between mass difference and mass bias, e.g., a power law. For radioactive decay corrections (i.e., on ^{37}Ar, ^{39}Ar, and ^{36}Ar$_{Cl}$) the decay constants used should be specified.

3.3. Negative values

Low abundance isotopes (typically ^{36}Ar, ^{37}Ar and/or ^{38}Ar) occasionally yield computed relative isotope abundances that are negative. While this is expected for a normal distribution roughly 50% of the time in the limit as the abundance tends to zero, numbers that are consistently more negative than uncertainty limits suggest mass spectrometry problems and/or inappropriate baseline or background corrections. Such results should not be replaced by zeros in the applicable column, as this masks the underlying problem. Ages calculated by setting negative values to zero should clearly indicate having been calculated in this way.

3.4. Step-heating

For stepwise heating experiments, the temperature or laser power for each step must be specified as well as the duration of heating. The latter may be a global variable and may not require specification for each heating step (see below). Extraction temperatures and times are important for any sample for which determining Ar degassing kinetics is, or could become, of interest.

3.5. Standards (neutron fluence monitors)

The reactor and port used for irradiation should always be specified, as should the presence or absence of Cd shielding. Information relating to the neutron fluence, i.e., *J*-value, must include the identity of the standard used (e.g., GA-1550) and the age assumed with a reference cited for that age. If multiple standards were used, the ages should be normalized to one standard and the intercalibration factors *R* (Renne et al., 1998) applied should be specified. This information is absolutely critical, because many different standards are in use and in some cases different ages are assumed for the same standard. Because neutron fluence is generally heterogeneous at some level, some basis for evaluating fluence gradients is necessary. The diverse irradiation schemes employed by different labs require some flexibility here, but if the three dimensional coordinates of all samples and standards in the irradiation package are provided then interpolated *J*-values may be determined. Thus in addition to the relative positions of standards and samples, the method (e.g., averaging, interpolation) of determining sample-specific *J*-values should be indicated.

3.6. Decay constants and isotopic abundances

The decay constants and isotope abundances used for age calculation must be specified (e.g., Steiger and Jäger, 1977). In addition to the decay constant(s) for ^{40}K, it is necessary to specify constants for ^{36}Cl, ^{37}Ar and ^{39}Ar. The most accurate values for some of these constants, and for the absolute ages of fluence monitors (standards) are currently under evaluation and efforts are underway to establish norms for their usage. In the interim we simply note the necessity of reporting the values and their uncertainties used. Uncertainties may be ignored if the ages are not being compared with ages determined by other means, but in such instances *it should be explicitly stated that this is the case*. For the air correction in model ages, the value of atmospheric ^{40}Ar/^{36}Ar (and ^{38}Ar/^{36}Ar insofar as it applies to the Cl correction on ^{36}Ar) needs to be specified and attributed to a specific reference – see also the importance of this to mass discrimination under *First-Order Corrections* above.

3.7. Irradiation-analysis time interval

One must know the time interval, or intervals in the case of multistep irradiations, between irradiation and analysis, in order to make decay corrections for ^{39}Ar, ^{37}Ar, and ^{36}Ar$_{Cl}$. This is relevant, for example, if one wants to recalculate ages based on revised values of one of the relevant decay constants or the ^{36}Cl/^{38}Cl production ratio. Additionally, it is sometimes useful to know *measured* sample/background ratios for isotopes (i.e., ^{37}Ar) that have undergone extensive decay before analysis. In most cases it suffices to report a time interval between the end of the last irradiation segment and the beginning of an analysis. If a multistep irradiation is sufficiently protracted, it may be necessary to account for the integrated production–decay history, e.g., Wijbrans and McDougall (1987).

3.8. Interference corrections

Interfering nuclear reactions require that Ar isotope data be corrected before ^{40}Ar/^{39}Ar ages can be calculated. The necessary corrections may be specified as isotope production ratios determined for chemically simple compounds such as synthetic salts or glasses, in the form $(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})_K$, where the subscript denotes the target element. Which of these corrections is most important depends on sample composition and neutron irradiation characteristics, so it is recommended to provide values and their uncertainties for $(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})_K$, $(^{38}\mathrm{Ar}/^{39}\mathrm{Ar})_K$, $(^{37}\mathrm{Ar}/^{39}\mathrm{Ar})_K$, $(^{39}\mathrm{Ar}/^{37}\mathrm{Ar})_{Ca}$, $(^{38}\mathrm{Ar}/^{37}\mathrm{Ar})_{Ca}$, and $(^{36}\mathrm{Ar}/^{37}\mathrm{Ar})_{Ca}$. The production ratio P (^{36}Cl/^{38}Cl) and its uncertainty should also be specified. At a minimum, a reference pertinent to the same reactor and conditions (e.g., with or without Cd shielding) should be cited if the supporting data are not included in the paper.

4. Nonessential information

Several quantities are routinely reported in ^{40}Ar/^{39}Ar data tables that are not fundamental, i.e., they can be derived from the minimal data described above by calculation, or are not specifically needed to compute an age. These include the percentage of ^{40}Ar that is radiogenic (%^{40}Ar*), the ^{40}Ar*/^{39}Ar$_K$, Ca/K, Cl/K, and even the model age (assuming an atmospheric or other initial ^{40}Ar) calculated from ^{40}Ar*/^{39}Ar$_K$ and the *J*-value. Reporting these values should be considered optional, though some of them may be convenient to interpretation of the data. Absolute argon abundances are not required for ^{40}Ar/^{39}Ar age computations, but are commonly useful for various purposes and it is recommended to report the estimated yield in moles for one isotope, and the basis for determining the conversion (i.e., the sensitivity). Non-SI units such as cc-STP are discouraged.

4.1. Data format

We do not intend to dictate the specific format for ^{40}Ar/^{39}Ar data reporting, although this is becoming increasingly important for populating databases. The purpose of this communication is simply

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[1] Contrary to popular belief, the atmospheric ^{40}Ar/^{36}Ar recommended by Steiger and Jäger (1977) is not the same as that reported by Nier (1950), as discussed by Renne et al. (2009).

to identify the information that should be reported. Table 1 shows one possible format fulfilling the requirements discussed here.

4.2. Hierarchy of variables

The various data specified above apply to variable numbers of mass spectrometric analyses. Decay constants, for example, will presumably always be global variables with the same values applied to all data in a given report. If all measurements result from irradiation in a specific reactor under similar conditions, the interference corrections may be global variables. *J*-values are likely to be specific to all analyses of a given sample. Discrimination and background corrections are likely to apply to batches of data acquired over a specific time interval. Extraction temperatures in general will be specific to each analysis. Heating duration may be global at the sample level or multiple sample level, and should be treated accordingly.

5. Data analysis

There are several approaches to determine an age from ^{40}Ar/^{39}Ar data. This communication does not intend to advocate any approach in preference to any other, but rather to note that some approach-specific details should be given for any means of calculating ages. Most generally, any measure of the best age derived from a number of analyses must specify what kind of calculation is being reported. For example, for plateau ages and pooled total fusion data, a weighted mean is often used in which the weight factor is the inverse variance of individual ^{40}Ar*/^{39}Ar$_K$ values. To avoid confusion with weighting based on other variables, such as %^{39}Ar, the weighting basis should be specified. Pooled statistics should provide a measure of data scatter relative to analytical precision, as embodied in the Mean Square of Weighted Deviates (MSWD) statistic (see e.g., Ludwig and Titterington, 1994) or the less *n*-dependent "probability of fit". Some additional requirements specific to several computation methods are given below.

5.1. Hierarchical error propagation

Sources of systematic error should be applied only to pooled data with random errors. Each of the three most widely used age metrics, *mean of multiple analyses, plateau age, and isochron age*, should be used to first compute a most probable value of ^{40}Ar*/^{39}Ar$_K$ and its uncertainty, and this uncertainty should then be propagated through the age equation with systematic errors (i.e., in *J* and the ^{40}K decay constant) factored into the calculation. For comparing different analyses of a single sample, e.g., in testing for a plateau in step-heating, all sources of error in the *J*-value should be ignored. However, when comparing samples with different *J*-values, whether or not they are from the same irradiation, analytical error in *J* (uncertainty in ^{40}Ar*/^{39}Ar$_K$ for the standard) should be treated as a random error. Failing to propagate systematic errors hierarchically produces spuriously low MSWD values.

5.2. Mean of multiple analyses

In addition to specifying what type of mean and weighting scheme, criteria for rejection of outliers should be stated clearly. These criteria may be based on composition (i.e., Ca/K and Cl/K), age, or other conditions specific to a given study. Where composition is used as a criterion for including or excluding analyses from an age calculation (including plateau and isochron ages), independent data (e.g., optical microscopy or electron microprobe analyses) should be provided. Where age is the criterion, the basis for discriminating results, i.e., for identifying outliers, should be given (e.g., a Student's *t* test).

5.3. Plateau age

Criteria for defining a plateau (e.g., number of contiguous steps, % of ^{39}Ar, confidence level of indistinguishability, MSWD) must be indicated, either explicitly or by reference (e.g., Fleck et al., 1977). The type of calculation used to represent the plateau age must be given, i.e., inverse variance weighted mean of plateau steps.

5.4. Isochron age

As with plateau ages, the definition of an acceptable isochron should be stated explicitly, and the isochron age calculation algorithm should be stated or referenced (e.g., Ludwig, 2003).

6. Concluding remarks

Our intention is to motivate researchers and journal editors to consistently provide the minimum information needed to enable maximum utility of ^{40}Ar/^{39}Ar data. This ideal has only rarely been approached in the past. We cast no aspersions at past departures from the ideal, as indeed we have all published data with less detail than is being called for here. Our experience is that most ^{40}Ar/^{39}Ar geochronologists recognize the need for improved norms along these lines, and that the additional effort required to achieve these goals is worthwhile. Some investment of effort (i.e., augmenting computer codes) will be required to facilitate routine reporting of all the data and metadata indicated herein, but the result will be an overdue upgrade in the utility of ^{40}Ar/^{39}Ar age information. This effort will also help the scientific community in the automated population of online databases as is becoming a future data policy requirement by many funding agencies.

Finally, we acknowledge that even the minimum data as described herein are not the full raw data typically processed by ^{40}Ar/^{39}Ar geochronologists to calculate ages from argon isotope measurements. Individual measurements of backgrounds and air pipettes could be provided rather than summarized as suggested here, and this may be worthy of future discussion. Inclusion of these results would typically expand the amount of data to be reported by 20–50%, and would require additional metadata regarding analytical conditions. There is still another level of detail to consider reporting, namely the most fundamental measurements routinely made in ^{40}Ar/^{39}Ar geochronology – baselines and peak heights as a function of time after equilibration in the mass spectrometer. This level of information would require about an order of magnitude more data to be reported, would require additional documentation of analytical conditions, and would be meaningfully useful to only a small number of specialists, hence is considered to be unnecessary at this stage.

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