THE EFFECT OF PARTIAL THERMAL RESETTING ON ^{40}Ar-^{39}Ar "PLATEAUS."
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Introduction: The ^{40}Ar-^{39}Ar technique is a powerful geochronology tool, particularly when dating thermal disturbance of a system. However, the question of what represents a robust determination of the time of a thermal event can be complicated. Here, we attempt to quantify the effect of partial resetting on a common variant of the technique, involving release of gas from a sample by stepwise heating.

The technique relies on the buildup of ^{40}Ar from the decay of ^{40}K, whose 1250 Ma half-life makes it appropriate for studying many events of planetary significance. In the ^{40}Ar-^{39}Ar technique, the sample is irradiated with neutrons to convert some stable ^{39}K to ^{39}Ar, so that the ^{40}Ar/K ratio can be determined by analyzing only Ar isotopes. A common approach is to then heat the sample to progressive higher temperature steps, analyzing the gas that comes out at each step and determining an apparent age (hereafter simply referred to as "age") for that step. These ages are then plotted against the cumulative fraction of ^{39}Ar released (Fig. 1). In an early attempt to determine what represents a robust age determination, [1] defined a "plateau" as a set of three or more consecutive steps with statiscally indistinguishable ages, reprenting 50% or more of the cumulative ^{39}Ar. Their definition of statistically indistinguishable ages was that no two of the ages in the plateau differed by more than a critical value *CV*, where $CV = 1.96\ (\sigma_1^2 + \sigma_2^2)^{½}$, with σ_1 and σ_2 representing the uncertainty in the individual ages.

However, when a sample that crystallized at a particular time is disturbed by a thermal event at a later time, no matter how small the event is, the ages of even the final steps are lower than the true age of the original event (e.g., [2] and Fig. 1), although the difference is small if the fraction of ^{40}Ar lost is small.

Jourdan and co-workers [3] have argued that the plateau should contain 70% of the cumulative ^{39}Ar released to be considered robust. Furthermore, they suggested that datasets where the "plateau" represents only 50% should be considered "mini-plateaus."

But is 50% really too small to be considered a real plateau? Is 70% enough, given that the plateau age will always be lower than the true age for any scenario involving partial thermal resetting? Here, we provide quantitative answers to how much the plateau age will differ from the true age under various conditions.

Methods: We calculated the release pattern for a sample with diffusion characteristics typical of meteoritic feldspar (E = 27 kcal/mol, $D_0/a^2 = 19.95\ s^{-1}$) under a heating schedule of 1ºC steps for 30 s at temperatures starting at 300ºC. This yields more than 650 steps that release at least 0.01% of the ^{39}Ar. The sample was assumed to have crystallized instantaneously 4000 Ma ago, and then experienced a thermal event at 1500ºC for some duration *t*, at a time 1, 1000, 2000, or 3000 Ma ago. The duration was varied to give a wide variety of amount of total loss of Ar in the event, which we calculated. It is important to note that for the questions we are addressing, the detailed diffusion characteristics, temperature and duration of the heating event, or laboratory heating schedule do not matter. The only parameters that matter are the times of the initial crystallization and the later thermal event, and the amount of loss in that event.

We then varied the duration of the thermal event (to vary the amount of loss) to get plateaus of various width, ranging from 30% to 70% of the total ^{39}Ar, in increments of 10%. Of course, the width of the plateau depends on the "height" H, the difference in age permitted across the plateau (Fig. 1 shows the 50% plateau for the 50% loss case). In a real experiment, this is determined by the uncertainties in the age determinations. Since we were using a rather idealized case, we simply took it to be the difference between the first step (lowest age) in the plateau and the age at 99.99% ^{39}Ar release (the highest age), as indicated in Fig. 1 for the 50% loss case. We found the loss amounts that yielded plateau "heights" of 10 Ma, 25 Ma, 50 Ma and 100 Ma for each plateau width for each resetting situation. We then calculated the "plateau age" by summing the total amount of ^{39}Ar and the total amount of ^{40}Ar released in the plateau and calculating the apparent age of that gas. In Figs. 2 and 3, we plot $\Delta T/H$, where ΔT is the difference between the plateau age and the actual age of crystallization, and H is defined above. Hence, a $\Delta T/H$ greater than 1 incidates the accuracy of the measured age is worse than the spread of apparent ages in the plateau. Figs. 2 and 3 plot the cases where the resetting event occurred at 1 Ma and 3000 Ma, respectively (the endmembers of the situations we considered). In each figure, there are four lines, representing H= 10 Ma, 25 Ma, 50 Ma and 100 Ma.

But how does the "height" in our simulations relate to the uncertainties in an actual experiment? Intuitively, one might think that a height of H might represent something like the 2σ uncertainty in the age determinations. We ran a Monte Carlo simulation of one particular situation, resetting at 3000 Ma leading to a 50% plateau with H = 10 Ma. We simulated a case with each "step" representing 5% of the cumulative 39Ar release. To do this, we first binned four sets of our 1°C steps (each bin containing at least 13 steps) that yielded 50-55%, 55-60%, 90-95% and 95-99.9% of the cumulative ^{39}Ar released, respectively. For each bin ("step"), we calculated the ideal age by summing the total ^{39}Ar and ^{40}Ar released in the bin. Note that these bins would, in the absence of statistical effects, give the two lowest and two highest ages in the plateau. We then tested 5000 cases, generating the simulated age for each of the bins by using a random number [4] within a Gaussian distribution with σ = 5 Ma. In 48% of the cases, at least two of the four bins differed by more than *CV*, close enough to 50% to suggest that the intuitive interpretation (H = 2σ) is correct to first order.

Results and Conclusions: Figs. 2 and 3 display some of the results. The most important result is that a 70% plateau has ΔT ~ 0.4H (~0.8σ), a 50% plateau has ΔT ~ H (~2σ). Thus both are different from the true age of crystallization, a factor that should be kept in mind in comparisons with other geochronology systems that may not have been affected by the thermal event. However, even the 50% is not far off – if uncertainties are quoted as 2σ, the true age is higher by roughly the uncertainty. However, 40% plateaus are low by at least 1.67H, 30% plateaus by at least 3.4H, so while it would be possible to build a model to determine the true age, it would be sensitive to the exact width of the plateau, and would be unlikely to be at all reliable.

It is also worth noting that the results are, to first order, independent of either the time of resetting (Fig. 2 and Fig. 3 are very similar) or the size of H (the points generally overlap for a given plateau width). In detail, ΔT increases for early thermal events (from 0.38H for a 70% plateau for 10 Ma for the 1 Ma event to 0.383H for the 3000 Ma event). Also, ΔT/H increases for larger H. The difference is small for the 70% plateau (from 0.380 for 10 Ma for the 1 Ma event to 0.396 for 100 Ma for the same event), but increases for smaller plateaus, up to 20% for the 50% plateau for 3000 Ma. Fig. 3 does not have points for 100 Ma for the 30% or 40% plateaus, because H is always <100 Ma for the last 40% of the release in that case.

Note that this entire analysis applies only to thermal resetting, not to chemical alteration, recoil during irradiation, multi-phase (or multi-diffusion-domain) samples, or excess ^{40}Ar.

References: [1] Fleck R.J., et al. (1977) *GCA 41*, 15-32. [2] McDougall I. and Harrison T.M. (1999) *Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method*. 2nd ed. [3] Jourdan F. (2012) *Austral. J. Earth Sci. 59*, 199-224. [4] https://www.random.org/gaussian-distributions/

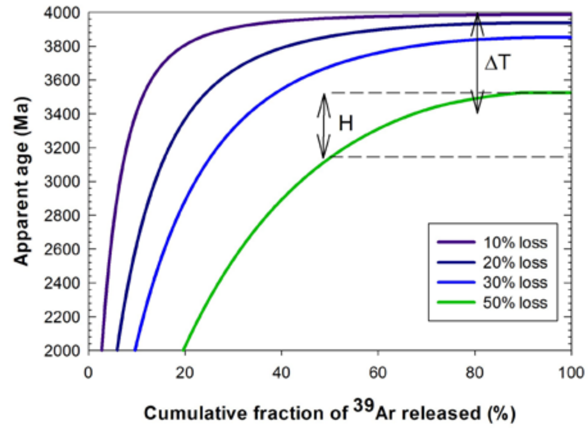

Fig. 1: Release patterns for sample that experienced various degrees of loss at 1 Ma. H and ΔT are explained in the text.

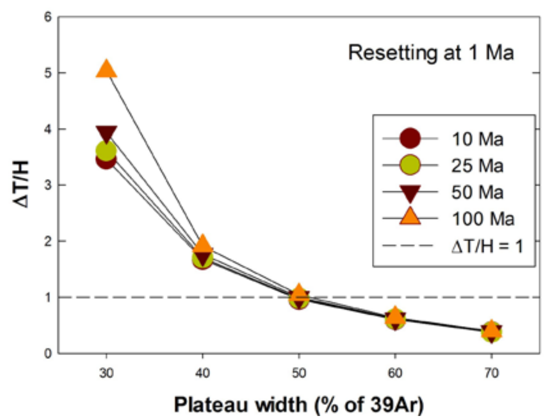

Fig. 2: ΔT/H (the error in age relative to the height of the plateau) for various sizes of H for a 1 Ma resetting event.

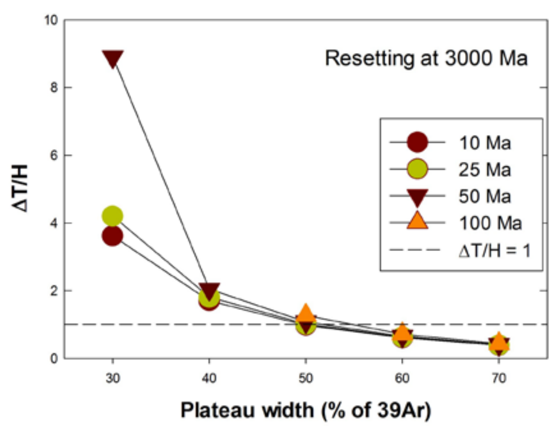

Fig. 3: ΔT/H for various sizes of H for a 3000 Ma resetting event.