Analysis of Thermal Conditions Required To Reset Ar-Ar Ages.

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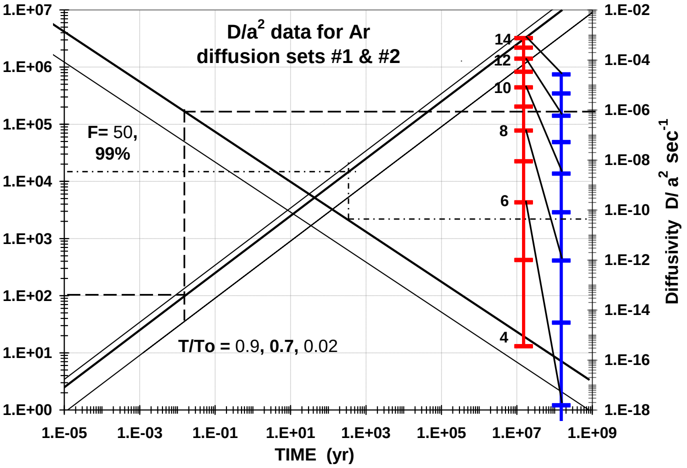
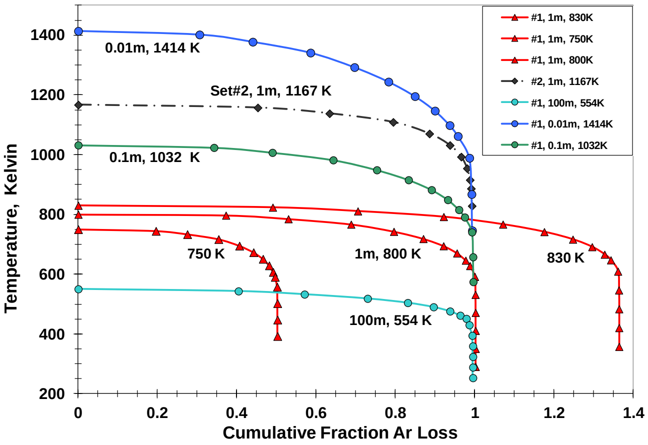
In resetting of ^{39}Ar-^{40}Ar ages by thermal events, including impact heating, the issue of what temperature is required often arises. Here I examine that question in detail and show that an enormous variability exists. Ar diffusion loss depends on a) temperature; b) the time period the sample is maintained at that temperature, or in the case of decreasing temperature, the cooling rate; and c) the diffusion characteristics for Ar in the host lattice, expressed as D/a^2 (D=diffusivity; a= diffusion distance before loss). The rate of heat loss from a body expressed as T/To (To= initial temperature and T= temperature at a later time t) is proportional to exp{-kt/r^2}, where k is the thermal diffusion constant for the material, t the elapsed time, and r the distance heat must travel before it is lost by radiation into space or conduction into colder, adjacent material. On a log-log plot of body size (e.g., radius of a sphere or half-thickness of a slab) versus elapsed time, specific values of T/To will define straight lines. On a log-log plot of D/a^2 versus elapsed time, the fraction of gas loss, F (or concentration (Co-C)/Co) also will be defined by straight lines [1]. Fig. 1 shows this combined plot for slabs of varying half-thicknesses (1 to 10^7 cm), where the three diagonal lines labeled T/To =0.9 ,0.7, and 0.02 give the time required to cool by 10%, 30%, and 98%, respectively. The diagonal lines labeled F= 50% and 99% show these amounts of Ar loss as a function of time and the diffusion parameter D/a^2. Because thicker slabs retain heat longer, they can produce significant Ar diffusive loss from a sample with lower D/a^2.

Unlike the thermal diffusion constant k, the gas diffusion parameter D is strongly temperature dependant. Fig. 1 plots two representative sets of Ar diffusion data as vertical bars arbitrarily positioned between time=10^7-10^8 years. Ar diffusion set #1 (red) has activation energy, Q=28 kcal/mole and D/a^2 at 1000^o Kelvin is 10^{-5} sec^{-1}. Ar diffusion set #2 (blue) has Q=45 kcal/mole and D/a^2 at 1000^o K is 10^{-7} sec^{-1}. Some temperatures (K) are labeled on data set #1, and tie lines connect these to the same temperatures on the #2 set. (For meteorite Ar, most experimental values of Q range ~20-60 kcal/mole, and D/a^2 at 1000K range ~10^{-4}-10^{-8} sec^{-1}. Terrestrial feldspars have similar values [2].) In Fig. 1, using the intersection of some elapsed time with each of the two sets of curves, the amount of gas loss, F, for a particular value of D/a^2 can be related to the size of the slab required to maintain sufficient heat to produce that gas loss [1]. The upper dashed line shows Ar diffusion set #1 at 600^{o}C (873K) and D/a^2 ~8 x10^{-7} sec^{-1} and predicts a required time of 0.015 years (X-axis) for 99% Ar loss. The intersection of this 0.015-yr time with the sloped lines giving T/To values of 0.7 and 0.02, extrapolated over to the scale giving slab half-thickness, gives values of ~100 and ~35 cm, respectively. Slabs of these half-thicknesses would cool by 30% and 98%, respectively, in 0.015 years. For Ar diffusion data set #2 (lower, dot-dashed line), D/a^2 at 873K is ~4 x10^{-11} sec^{-1}, 99% Ar loss time becomes ~300 years, and the slab half-thickness for cooling over this longer time is ~50-130 meters.



However, in Fig. 1 the diagonals for fractional diffusion loss as a function of time assume constant temperature and D/a^2, whereas the lines for cooling of a slab represent falling temperature and D/a^2. To evaluate this effect, I selected several initial temperatures and half-thick slabs and utilized Ar diffusion sets #1 and #2. I used the cooling equation to divide the falling temperature as a function of time into many increments across T/To values of 1.0 to 0.02, assuming a final cool-down temperature of 200 K, and calculated the value of D/a^2 for each decreasing temperature increment [3]. D/a^2 values were summed across all temperature increments. Results are shown in Fig. 2, where each curve defines the fraction of Ar loss as a function of decreasing temperature. (Figs. 1 & 2 apply to the center of these slabs, and positions closer to the edges would experience somewhat faster cooling [4].) For a half-thick slab of 1 meter, Ar diffusion set #1, and initial temperatures of 750, 800, and 830 K, an initial temperature of 800 K is just sufficient to produce 100% Ar loss, whereas the other temperatures produce ~50% Ar loss and ~136% Ar loss. Importantly, for 800 K, ~80% of the Ar loss occurs by the time T/To has fallen to 0.9, or 740K (=0.9 x(800-200) +200), and ~99% of the Ar diffusive loss occurs by the time T/To =0.7 (620K). The same calculation for a 1 m slab and Ar diffusion data set #2 predicts that a minimum initial temperature of 1167 K is required to produce 100% Ar loss, and about 89% of the total Ar has been lost by the time T/To=0.9 (1070 K). Assuming diffusion data set #1 and a 100 m half-slab, the required initial temperature is 554 K, and ~98% of the total Ar loss occurs by the time T/To reaches 0.7 (448K). For the 0.1 m slab (initial temperature of 1032K), ~98% of the total Ar loss has occurred by the time T/To=0.7 (782K). For a 1 cm half-thick slab, which requires a much higher initial temperature (1414 K) and for which cooling occurs rapidly, fractional Ar loss is ~70% and ~96% by the time T/To reaches 0.9 (1290K) and 0.7 (1050K), respectively. Note that in each of the cumulative Ar loss curves in Fig. 2, almost all of the Ar loss occurs early in the cooling process when T/To decreases from 1.0 to 0.7, and little Ar loss occurs subsequently. This situation occurs because of the large sensitivity of D/a^2 on temperature.



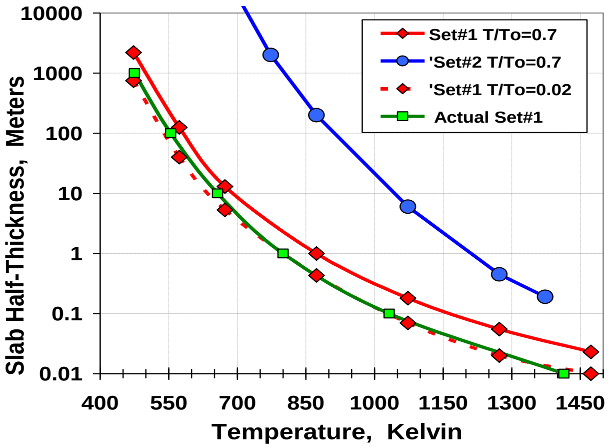


Fig. 1 was used to determine curves of approximate slab half-thickness required to lose 99% of the Ar as a function of initial temperature, and these are presented in Fig. 3. The two red-diamond sets of curves assume Ar diffusion data #1 and T/To =0.7 (solid) and 0.02 (dashed). The blue-circle curve above assumes Ar diffusion data #2 and T/To = 0.7. The curves for T/To of 0.7 and 0.02 (diffusion data #1) indicate required temperatures for Ar loss in a 1-m slab of ~880K and ~790K, respectively, whereas the "actual" calculated temperature is 800K (Fig. 2). For a 100 m slab, curves for T/To= 0.7 and 0.02 correspond to temperatures of ~574K and ~535K, respectively, whereas the calculated temperature from Fig. 2 is 554K. **The relative position of these three curves demonstrates that the D/a^2 of a particular sample is much more important in determining Ar loss than the uncertainty in selecting a specific T/To curve in Fig.1.** The green-squares "actual" curve in Fig. 3 was constructed from the data in Fig. 2. For half-thick slabs of 1 km to 1 m, this "actual" curve lies slightly above the curve for T/To=0.02. For half-thick slabs <1 m, the "actual" curve closely follows the curve for T/To=0.02. For all slabs with half-thickness ≥1 meter, at least 95% of the Ar has been lost by the time T/To=0.7. Fig. 3 shows that for the Ar diffusion data set #1, quantitative Ar loss can occur in a 1 km half-thick slab at a temperature as low as ~500 K, whereas for a 10 cm half-thick slab a temperature of ~1050 K would be required. For material possessing increased difficulty for Ar diffusion, e.g., data set #2, the temperatures required for quantitative Ar loss for the same slab size increase by a factor of about 300 K. This analysis again emphasizes the sensitivity of Ar diffusive loss to both temperature and D/a^2 for a given sample.

From this analysis I conclude that if the Ar diffusion characteristics of a sample as a function of temperature are approximately known, Fig. 1 can be used to relate fractional Ar loss to the thickness of an impact deposit as a function of the cooling temperature. For 99% Ar loss and knowing one parameter, one can find the others using the curves for 99% Ar loss and T/To =0.7 and 0.02, where the difference between the two curves represents the last few percent of Ar diffusive loss. At T/To=0.7, the Ar-Ar age spectrum may be slightly sloped. The relationship between temperature and D/a^2 for Ar diffusion is critical and should be determined from experimental sample data, and this relationship is the most sensitive parameter in determining cooling time and thickness of an impact deposit required to produce significant Ar loss.

[1] Park et al., 2008, JGR Planets, 113, E08007, doi:10.1029/2007JE003035; [2] Lovera et al., 1997, GCA 61, 3171; [3] Langerwall & Zimen, 1964, *EURAEC Report No. 772* (European Atomic Energy Community) [4] Bogard & Garrison, 2008, EPSL 273, 386.

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