# AN ~ 4.35 Ga Ar-Ar AGE FOR GRA 8 AND THE COMPLEX CHRONOLOGY OF ITS PARENT BODY.

J. Park[1,2], L. E. Nyquist [3], D. D. Bogard[3], D. H. Garrison[4], C.-Y. Shih[4] and Y. D. Reese[5]. [1]Lunar and Planetary Institute, 3600 Bay Area Blvd. Houston, TX 77058, [2]NASA-MSFC, Huntsville, AL 35812 & Univ. Alabama @ Huntsville, 35805. (Jisun.park-1@nasa.gov) [3]KR/NASA Johnson Space Center, Houston, TX 77058. [4]ESCG Jacobs-Sverdrup, Houstson, TX 77058. [5]Mail Code JE-23, ESCG/Muniz Engineering, Houston, TX, 77058.

**Introduction:** GRA06128 and GRA06129 (hereafter GRA 8 and GRA 9) are partial melts of a parent body of approximately chondritic composition [1-3]. We [4,5] reported a conventional $^{147}Sm$-$^{143}Nd$ isochron age of 4.559±0.096 Ga and a $^{146}Sm$-$^{142}Nd$ model age of 4.549±0.036 for combined data for the two rocks. Plagioclase plus whole rock and leachate (~phosphate) samples gave a secondary $^{147}Sm$-$^{143}Nd$ age of 3.4±0.4 Ga [5]. An $^{39}Ar$-$^{40}Ar$ age of 4.460±0.028 Ga [3,6] was interpreted by [3] as dating metamorphism in GRA 9. We report $^{39}Ar$-$^{40}Ar$ ages in the range ~4344-4366 Ma for GRA 8, establishing similar but different $^{39}Ar$-$^{40}Ar$ ages for the two rocks, consistent with their different Sr-istopic systematics [5], and discuss these ages in the context of the complex sequence of events that affected these samples (*cf.* [3]).

**$^{39}Ar$-$^{40}Ar$ Stepped Ar-Release Ages for GRA 8:** We did a stepped-temperature Ar extraction (49 steps) of a plagioclase separate of GRA 8 (12.7 mg) of low magnetic susceptibility (Fig. 1). Small age variations occurred among "phases" with different K/Ca at low, intermediate, and high extraction temperatures, and the summed age is 4354 Ma. Partitioned according to the fraction of $^{39}Ar$ released, the calculated ages varied from 4326±18 to 4344±14 to 4362±18 Ma (1█ for 4-14%, 14-47%, and 52-96% $^{39}Ar$ released, resp. A single temperature step for 47-52% of the $^{39}Ar$ release appeared to mark a transition in the gas release mechanism as also seen in an Arrhenius plot constructed from the data (Fig. 2).
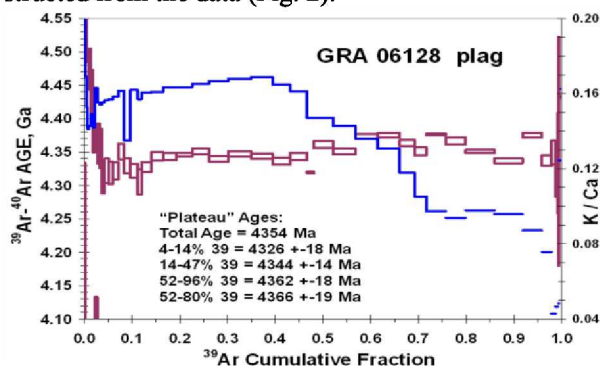


Figure 1. Calculated $^{39}Ar$-$^{40}Ar$ ages as a function of the cumulative fraction of $^{39}Ar$ released.

**Arrhenius Plot for Stepped Ar-Release:** In Fig. 2 values of the diffusion parameter $D/a^2$ calculated for each temperature interval up to 940°C (gray circles) are plotted vs. reciprocal absolute temperature (T)

expressed as 1000/T. Two diffusion regimes can be mathematically decoupled as shown by the two straight lines with the shallowest and steepest slopes (also see Fig. 1). An abrupt transition in degassing occurs at 1000/T ~0.82 (T =940°C), and the diffusion rate and activation energy decrease. Although the K/Ca ratio lies near K/Ca =0.13 reported for plagioclase by EMPA [3], a change in K/Ca also begins near the 940°C transition. We interpret this transition as due to a structural change in the K-bearing phases. We suggest this change was either induced by the laboratory heating or is relict from sub-solidus reequilibration on the parent body.
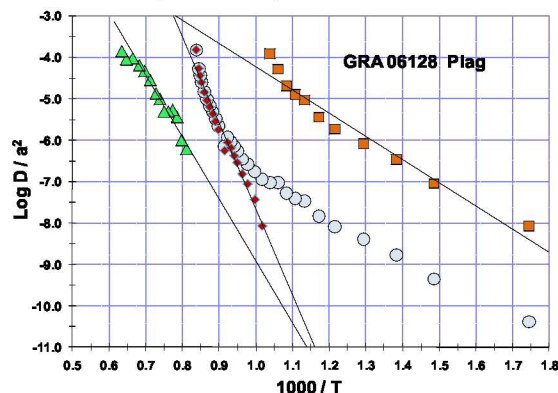


Figure 2. Arrhenius diffusion plot of log $D/a^2$ vs. reciprocal temperature (in K) for $^{39}Ar$ release from GRA 8.

**Discussion:** Viewed in isolation, these $^{39}Ar$-$^{40}Ar$ data are well-defined and could be interpreted as giving a relatively unambiguous chronology for GRA 8 consisting of intial formation at 4366±19 Ma ("most reliable" high-T age for 52-80% $^{39}Ar$ release) followed by final closure to Ar loss at 4344±14 or 4326 ±18 Ma as a result of subsolidus recrystallization (*cf.* [3]). However, consideration of all the chronological data for GRA 8/9 presents a more complicated picture.

*Comparison to $^{39}Ar$-$^{40}Ar$ age of GRA 9.* Fernandes [3,6] reports the $^{39}Ar$-$^{40}Ar$ age of GRA 9 to be 4460±28 Ma. Thus, the $^{39}Ar$-$^{40}Ar$ ages of GRA 8 and 9 appear to be clearly resolved, which we suggest is the result of different thermal histories for the two samples.

*Comparison to $^{147}Sm$-$^{143}Nd$ isochron ages.* The $^{147}Sm$-$^{143}Nd$ data for GRA 8 and 9 are complex (Fig. 3). With the assumption that both bulk rocks remained *closed* isotopic systems, the data appear to show a secondary age of 3.4±0.4 Ga for plagioclase/whole rock superimposed on a primary age of 4559±96 Ma

for pyroxene/whole rock [5]. However, if the isotopic system were *open* due, e.g., to the introduction into a mainly plagioclase/pyroxene cumulate rock of a phase from which phosphate crystallization occurred, the necessity to include the "whole rock" (WR) data in a primary isochron fit would be removed. In this case, a plagioclase plus pyroxene tie-line gives an apparent age of 4.24±0.07 Ga (2■ nearly within error limits of the intermediate-temperature $^{39}$Ar-$^{40}$Ar age of 4344±28 (2■ However, a similar exercise for GRA 9 results in an apparent age of 4.00±0.11 Ga. This age is younger than the $^{39}$Ar-$^{40}$Ar age, but the first ~11% of the gas release gives a hint of a younger age near ~4.0 Ga [6].
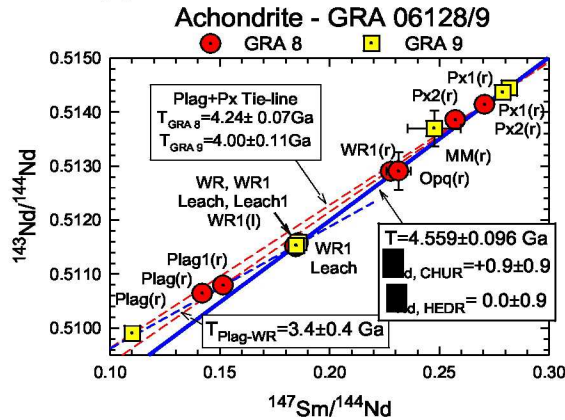


Figure 3. $^{147}$Sm-$^{143}$Nd data for GRA 8 and 9 [5]. Pyroxene-plagioclase tie-lines have been added to show the effect of the leachate (~phosphate data).

*Comparison to $^{87}$Rb-$^{86}$Sr data.* The $^{87}$Rb-$^{86}$Sr isochron ages are relatively poorly defined because of terrestrial contamination and the modest range in $^{87}$Rb/$^{86}$Sr ratio [5]. Fig. 4 shows the Rb-Sr data in a (T,I$_{Sr}$) plot for those data judged to be most reliable. The $^{39}$Ar-$^{40}$Ar ages for GRA 8 and GRA 9 are plotted within the error parallelograms for the Rb-Sr data. The two data sets are consistent in showing that (a) GRA 8 and 9 differ, and (b) the $^{39}$Ar-$^{40}$Ar ages are close to the nominal ages obtained from the Rb-Sr isochrons. We noted previously that evolution from ($^{87}$Sr/$^{86}$Sr)$_I$ ~0.698934 for CAI at typical chondritic $^{87}$Rb/$^{86}$Sr (■ ~0.82 would require ~15 Ma for GRA 9 and ~40 Ma for GRA 8, resp. [5]. With the same assumptions, but treating the $^{39}$Ar-$^{40}$Ar ages as crystallization ages requires a precursor with lower $^{87}$Rb/$^{86}$Sr ~ 0.24 like that in CV chondrites. Interestingly, Arai et al. [7] suggested a volatile-rich carbonaceous chondrite parent asteroid for GRA 01628/9.

*Alternative scenarios.* Shearer et al. [3] recognize three major post magmatic events: (1) subsolidus reequilibration to form a granoblastic texture; (2) reaction between the primary magmatic phases and either a residual melt or a fluid phase; (3) low temperature alteration along grain boundaries and fractures. They equate the ~4.46 Ga $^{39}$Ar-$^{40}$Ar age of GRA 9 [3,6] to (1) above. Because $^{40}$Ar would be rapidly outgassed at the corresponding temperatures, we equate subsolidus equilibration to the 4344±14 Ma age obtained for GRA 8 at intermediate temperatures. We furthermore equate the younger 3.4±0.4 Ma secondary Sm-Nd isochron to process (2) above. Low temperature alteration probably is manisfested only as "isotopic disturbances". Two alternatives for the primary crystallization ages of GRA 8 and 9 are: (1) Both formed ~4.56 Ga ago, and $^{39}$Ar-$^{40}$Ar ages between ~4.56 Ga and ~4.34 Ga ago are due to slow cooling of the parent body or separate impact events. (2) The crystallization age of each stone may be close to its $^{39}$Ar-$^{40}$Ar age, i.e., for GRA 8 the high temperature age of 4362±18 Ma. This interpretation implies late magmatism on the parent body, and allows easy interpretation of the Rb-Sr data, but requires the ~4.56 Ga ages to have been carried into the rocks via phosphates introduced via open system reactions with external melts or fluids. Shearer et al. [3] identify merrillite as one of the primary magmatic phases favoring (1) above, but Treiman et al. [1] note phosphate replacing pyroxene and merrillite replacing apatite, perhaps a hint of open system processes permitting (2) above.
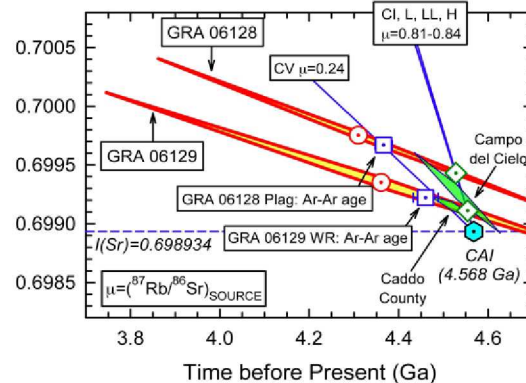
Figure 4. (T, I$_{Sr}$) for GRA 8 and 9 showing the location of the $^{39}$Ar-$^{40}$Ar ages of these samples within the corresponding error parallelograms. Updated from [5].

**References:** [1] Treiman A. H. et al. (2008) LPS XXXIX, Abstract #2214. [2] Day J. M. D. et al. (2009) *Nature, 457,* 179-182 [3] Shearer C. K. et al. (2009) *GCA,* doi:10.1016/j.gca.2009.10.029. [4] Nyquist L. E. et al. (2008) *Meteoritics & Planet. Sci., 43,* A119. [5] Nyquist L. E. et al. (2009) LPS XXXX, Abstract #1290. [6] Fernandes V. A. and Shearer C. K. (2010), this meeting. [7] Arai T. et al. (2008) LPS XXXIX. Abstract #2465.