AN ~ 4.35 Ga Ar-Ar AGE FOR GRA 8 AND THE COMPLEX CHRONOLOGY OF ITS PARENT BODY.
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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 147Sm-143Nd isochron age of 4.559±0.096 Ga and a 146Sm-142Nd 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 147Sm-143Nd age of 3.4±0.4 Ga [5]. An 39Ar-40Ar age of 4.460±0.028 Ga [3,6] was interpreted by [3] as dating the fraction of 39Ar released, the calculated ages vs. reciprocal absolute temperature (T) are plotted vs. reciprocal absolute temperature (T) to show a secondary age of 3.4±0.4 Ga for plagioclase/whole rock superimposed on a primary age of 4559±96 Ma 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 1. Calculated 39Ar-40Ar ages as a function of the cumulative fraction of 39Ar released.

Arrhenius Plot for Stepped Ar-Release: In Fig. 2 values of the diffusion parameter D/a2 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/a2 vs. reciprocal temperature (in K) for 39Ar release from GRA 8.

Discussion: Viewed in isolation, these 39Ar-40Ar data are well-defined and could be interpreted as giving a relatively unambiguous chronology for GRA 8 consisting of initial formation at 4366±19 Ma (“most reliable” high-T age for 52-80% 39Ar 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 39Ar-40Ar age of GRA 9. Fernandes [3,6] reports the 39Ar-40Ar age of GRA 9 to be 4460±28 Ma. Thus, the 39Ar-40Ar 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 147Sm-143Nd isochron ages. The 147Sm-143Nd 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 4.2.4±0.07 Ga (2), nearly within error limits of the intermediate-temperature 39Ar-40Ar age of 4.344±0.07 Ga (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 39Ar-40Ar age, but the first ~11% of the gas release gives a hint of a younger age near ~4.0 Ga [6].

**Achondrite - GRA 06128/9**

![Graph](attachment:image.png)

**Figure 3.** 147Sm/144Nd 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 87Rb-86Sr data.** The 87Rb-86Sr isochron ages are relatively poorly defined because of terrestrial contamination and the modest range in 87Rb/86Sr ratio [5]. Fig. 4 shows the Rb-Sr data in a (T, ISr) plot for those data judged to be most reliable. The 39Ar-40Ar 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 39Ar-40Ar ages are close to the nominal ages obtained from the Rb-Sr isochrons. We noted previously that evolution from (87Sr/86Sr) = 0.7048934 for CAI at typical chondritic 87Rb/86Sr (0.2) would require ~15 Ma for GRA 9 and ~40 Ma for GRA 8, resp [5]. With the same assumptions, but treating the 39Ar-40Ar ages as crystallization ages requires a precursor with lower 87Rb/86Sr ~ 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 39Ar-40Ar age of GRA 9 [3,6] to (1) above. Because 40Ar would be rapidly outgassed at the corresponding temperatures, we equate subsolidus equilibration to the 4.344±0.14 Ma age obtained for GRA 8 at intermediate temperatures. We furthermore equate the younger 4.3±0.4 Ma secondary Sm-Nd isochron to process (2) above. Low temperature alteration probably is manifested 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 39Ar-40Ar 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 39Ar-40Ar age, i.e., for GRA 8 the high temperature age of 4.362±0.18 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.

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**Figure 4.** (T, ISr) for GRA 8 and 9 showing the location of the 39Ar-40Ar ages of these samples within the corresponding error parallelograms. Updated from [5].