^{39}Ar-^{40}Ar EVIDENCE FOR AN ~4.26 GA IMPACT HEATING EVENT ON THE LL PARENT BODY.

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Introduction: Miller Range 99301 is a type 6, unbrecciated LL chondrite [1]. MIL 99301 is of interest because some compositional and petrographic features suggest it experienced rather high shock grades, whereas other features suggest it is relatively unshocked. Inconsistent shock indicators could be explained if MIL 99301 was shocked but then partly annealed by heat produced by impacts on the parent body [1 and references therein]. The hypothesis that MIL 99301 experienced high temperature metamorphism (type 6) followed by a later shock event that heated, but did not melt, the constituent feldspar [1] can be evaluated using ^{39}Ar-^{40}Ar chronology. This is because ^{39}Ar-^{40}Ar ages of shocked ordinary chondrites are generally <4.2 Ga [2-5], whereas ^{39}Ar-^{40}Ar ages of unshocked meteorites are generally older, and between 4.52 - 4.38 Ga [6].

Petrography Evidence to suggest MIL99301 experienced high shock grades includes: (1) extensive silicate darkening, typical of shock grades S3-S6; (2) chromite-plagioclase assemblages and thin chromite veins, characteristic of S4-S6; and (3) low-Ca clinopyroxene grains, characteristic of shock grades S3-S6 [1, and references therein].

Contrasting evidence from plagioclase and olivine grains suggests MIL 99301 experienced much lower shock grades. There are two feldspar phases in MIL 99301: a coarsely crystalline variety (mean composition of $Ab_{83.1}$, $Or_{5.8}$), and a finer-grained variety, which is only slightly more CaO-rich [1]. The crystalline plagioclase grains in MIL 99301 have sharp optical extinction. According to Stöffler et al. [7], plagioclase develops undulatory extinction at shock grades of ~S2 and becomes partially isotropic at S4. At higher grades of S5 or S6, plagioclase should have transformed into maskelynite, which is optically isotropic [7]. The plagioclase textures appear to suggest that MIL 99301 experienced very low, ~S1 shock levels [1]. Olivine also appears to have experienced low shock grades. Most ordinary S3 chondrites exhibit planar fractures and undulatory extinction. At higher levels (S4), mosaicism begins to develop, and at still higher shock grades (S5-6), planar fractures and planar deformation features form [7]. However, nearly every olivine grain in MIL 99301 exhibits sharp optical extinction [1]. Thus, the plagioclase and olivine appear to have shock grades of S1 according to the criteria of Stöffler et al. [7]. Because the ^{39}Ar-^{40}Ar method dates the age of K-bearing phases, if the plagioclase grains have been annealed by heat produced during impact events to type 4 metamorphic conditions [1], a relatively young Ar-Ar age may be expected.

Ar-Ar Chronology. A plot of ^{39}Ar-^{40}Ar age and K/Ca ratios versus the cumulative fraction of ^{39}Ar released during stepwise temperature extractions of a whole-rock sample of MIL99301 is shown in Fig. 1. A substantial decrease in ^{36}Ar/^{38}Ar and ^{36}Ar/^{37}Ar ratios (not shown) over the first several extractions indicate the release of adsorbed terrestrial Ar, which may account for the higher Ar-Ar ages at low fractional ^{39}Ar release. Between ~6% and 78% of the ^{39}Ar released the age uniformly increases from 4.16 Ga to 4.26 Ga and is indicative of a small amount of diffusive loss of ^{40}Ar, possibly from Antarctic weathering. A slight decrease in age for two extractions at ~80% ^{39}Ar released is probably due to release of ^{39}Ar that was recoil-implanted into grain surfaces of pyroxene during irradiation. Above 83% ^{39}Ar released the Ar-Ar age rapidly increases to a quasi-age plateau of ~4.52 Ga for four extractions releasing 11% of the total ^{39}Ar. Changes in the rate of release of ^{39}Ar with extraction temperature suggests that those extractions releasing above 83% ^{39}Ar release constitute a distinct K-bearing phase possessing different Ar diffusion properties. The entire Ar age spectrum does not resemble that expected for Ar loss from a single K-bearing phase.

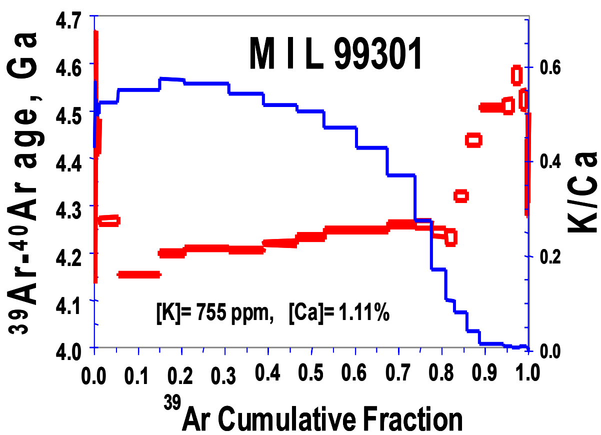

Figure 1. ^{39}Ar-^{40}Ar age spectrum, showing age (red rectangles, primary Y axis) and K/Ca ratio (stepped line, secondary Y axis) versus fractional ^{39}Ar released. The phase that degasses above ~83% of the ^{39}Ar preserves an older age (~4.52 Ga) than the phase that degasses at < 80% (< ~4.26 Ga).

We interpret this Ar-Ar age spectrum as follows. The older age of ~4.52 Ga dates the time of post-formational thermal metamorphism of the parent body, which for type 6 chondrites occurs at temperatures of 820-930°C [8]. The LL-6 portion of the parent body then experienced significant impact heating 4.20-4.26 Ga ago, where 4.26 Ga is the age shown by two extractions releasing 67-78% of the ^{39}Ar. The exact time depends on whether the the K-bearing phase that degasses between ~0-83% ^{39}Ar released was substantially or totally degassed by this heating event. It is however clear that this heating only partially degassed Ar from the K-bearing phase that degasses at higher temperatures between ~83-100% ^{39}Ar release. Subsequent Antarctic weathering produced small additional losses of ^{40}Ar from low-temperature sites. A substantial impact on the LL parent body is the only reasonable cause of a heating event long after parent body formation.

Thermal Model for MIL99301. We used the ^{39}Ar abundances as a function of stepwise temperature release to calculate diffusion parameters D/a^2 for our sample of MIL99301 [9]. Because the Ar isotopic data indicate ^{39}Ar release occurred from two distinct diffusion domains, as discussed above, we made these D/a^2 calculations separately for the phase releasing 0-83% of the total ^{39}Ar and the phase releasing 83-100% of the ^{39}Ar. An Arrhenius plot of D/a^2 versus reciprocal temperature for the lower temperature phase is linear for 10 extractions releasing ~30-83% of the total ^{39}Ar and yields an Ar activation energy of ~34 Kcal/mole. The higher T phase gives a roughly linear, but less well defined Arrhenius plot which is offset toward lower D/a^2 values compared with the low-T phase. The Ar activation energy for the high-T phase, ~38 Kcal/mole, is only slightly higher than that for the low-T phase. This suggests that the different Ar diffusion characteristics of the two K-bearing phases is produced by different mean grain sizes, possibly the result of the second annealing phase, rather than significantly different mineralogy, and is consistent with petrographic observations described above.

Equations for heat loss and gas diffusion contain analogous mathematical terms that include time as the common parameter. Thus, by making certain simplifying assumptions, we can construct a thermal model to constrain the post-shock thermal environment of MIL 99301 on the parent asteroid. This model combines the thermal cooling times of slabs of varying thicknesses with the times required to lose some fraction of the total Ar from a sample as a function of Ar diffusivity, D/a^2 [e.g., 3]. We assume that the impact event which produced the shock features in MIL99301 uniformly heated a zone beneath the crater to an initial temperature of ~600°C. This temperature derives from petrographic observations [1] that the post-shock metamorphism experienced by MIL99301 is similar to that observed in type 4 chondrites [10]. From extrapolations of the linear trends defined by the Arrhenius data for ^{39}Ar to a temperature of 600°C, we obtain values for D/a^2 of ~3 x10^{-7} for the low-temperature, K-bearing phase and ~3 x10^{-9} for the high-temperature phase. We note from the Ar age spectrum (Fig. 1) that the low-T phase apparently lost >90% of its radiogenic ^{40}Ar at 4.20-4.26 Ga, and that the high-T phase apparently lost ≤50% of its radiogenic ^{40}Ar at this time. Inserting these values for fractional ^{40}Ar loss and D/a^2 at 600°C into our thermal model, the low-temperature Ar data indicate a slab thickness of ~3 meters, and the less precise high-temperature data suggest a slab thickness of ~8 m. Thus, we suggest that following impact, MIL99301 resided ~4 m beneath the crater floor and was heated to ~600°C. The initial cooling rate for MIL99301 would have been relatively fast, ~6x10^{-5} °C/s, so that the the K-Ar chronometer would have become closed to diffusive Ar loss relatively early in the cooling process.

Conclusions. We suggest that, following an impact at about 4.20-4.26 Ga that produced the secondary metamorphism, MIL99301 resided several meters beneath the floor of a medium-sized crater on the LL parent body. The model used here assumes MIL 99301 resided in a uniformly heated unit beneath the crater, whereas in reality the heating of material beneath the crater was probably heterogeneous. Nevertheless, this thermal model seems quite consistent with post-shock metamorphism of MIL99301 beneath an impact crater as opposed to earlier metamorphism deep within the parent body. The ^{39}Ar -^{40}Ar ages are therefore consistent with post-shock annealing of some of the K-bearing feldspar in MIL 99301.

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