Progress Towards Turning Ar-Ar Chronology of Ordinary Chondrites into Thermochronology. J. R. Weirich[1], C. E. Isachsen[2], T. D. Swindle[1,2], C. Li[2], and R. T. Downs[2]. [1]University of Arizona, Department of Planetary Sciences, 1629 E. University Blvd., Tucson AZ, 85721, [2]University of Arizona, Department of Geosciences, 1040 E. 4th St., Tucson AZ, 85721.

Introduction: Extensive Ar-Ar (a variation of K-Ar) data has been collected for the ordinary chondrites, and with this data the community has been able to grossly recreate the impact history of various parent bodies. Most attention has been focused on the highly shocked chondrites, because they are most likely to have their Ar-Ar ages completely reset by an impact. However, partially reset ages can give insight into the time-temperature history of a meteorite, but only if we know the diffusion parameters of the potassium (K) bearing minerals. Mineral separates of ordinary chondrites are not usually performed due to their limited availability and fine-grained nature. Instead, whole rock samples are usually analyzed.

Whole rock samples are often complex, and indeed two releases of Ar have been seen in nearly every analyzed meteorite. One is below ~1000 °C and has a much higher K/Ca ratio compared to the release above ~1000 °C. While the low temperature (T) release is almost certainly Na-rich feldspar or albitic glass, identification of the high T release has proven elusive. What we do know is that shock seems to convert the low T release into the high T release [1]. Possible mechanisms include incorporation of K into pyroxene (Pyx) or Ca-rich feldspar [1], and enclosure of feldspar in pyroxene or olivine [2].

Weirich et al. (2010) [3] showed that experimental shock did change the Ar diffusion parameters of feldspar, but by making it an even lower T mineral, not higher. The Ar diffusion parameters of pyroxene, but not olivine, seem to grossly match previous values of the high T release, regardless of the shock pressure. To compliment the Ar diffusion parameters of shocked feldspar, pyroxene, and olivine, we measured the Ar diffusion parameters of the host material of the L6 impact melt breccia Chico [4], and the moderately shocked (S4) L6 Northwest Africa (NWA) 091 [5]. Additionally, a K mass balance was performed on Chico, and we used Raman spectroscopy on the feldspar of Chico to determine the structural state.

Procedures:

K mass balance/mineral abundance. We used the Cameca SX-50 at the University of Arizona to make X-ray elemental maps of Chico. These were used to determine modal abundance of major minerals. Point analyses with the same instrument determined the elemental abundance of major silicate minerals. These two data sets were used to perform a K mass balance.

Raman spectroscopy. We used the Thermo Nicolet Almega microRaman system at the University of Arizona with an excitation wavelength of 532 nm and partial polarization to identify the structural state of the feldspar in Chico.

Ar diffusion: Samples were wrapped in Al foil, irradiated at the CLICIT reactor at Oregon State University for 35 hours (which converts ^{39}K to ^{39}Ar and ^{40}Ca to ^{37}Ar), and analyzed on a VG5400 at the University of Arizona via step heating in a resistance furnace. The diffusion equation as a function of T is

$$\frac{D}{a^2} = \frac{D_0}{a^2} \bullet e^{\frac{E}{RT}}$$

, where E is the activation energy, D_0 is the frequency factor, and "a" is the diffusion distance. When plotted as log (D/a^2) vs. 1/T, this equation forms a straight line whose slope is proportional to E and whose intercept is log (D_0/a^2). Because the diffusion distance is often not known in a sample, E is a better discriminator between structural domains. Duplicate temperature steps were used to make sure multiple size domains were not outgassing simultaneously, and diffusion parameters were measured via the method developed by [6]. To ensure accurate measurements, different diffusion domains were mathematically separated, and the diffusion parameters for both ^{39}Ar and ^{37}Ar were determined.

Results:

K mass balance. K elemental maps of Chico host show two concentrations of K. One is of an oligoclase composition, the other is a non-stoichiometric feldspathic phase enriched in K. The pyroxene and olivine had no measurable K.

Modal mineral abundances were typical for L chondrites. While the K concentration of the K-enriched phase is ~4 times higher than the oligoclase-like phase, the very low abundance of the K-enriched phase (<0.02 wt%) means that it only accounts for ~1% of the total K in the meteorite. For pyroxene and olivine, if we use a generous upper limit of 50 ppm K, they still only account for ~10% of the K in the meteorite, though there is no evidence they contain any K. The oligoclase-like phase seems to dominate the K budget of the meteorite, giving a whole rock K abundance of ~490 ± ~120 ppm.

Raman Spectroscopy. 20 Raman spectra were taken of feldspar in the host material of Chico. All were similar to the spectrum shown in the top of Fig. 1, with an oligoclase standard at the bottom for reference.

While the two spectra shown in Fig. 1 are very similar, Chico feldspar has line broadening that indicates disordered (but still structural) feldspar.

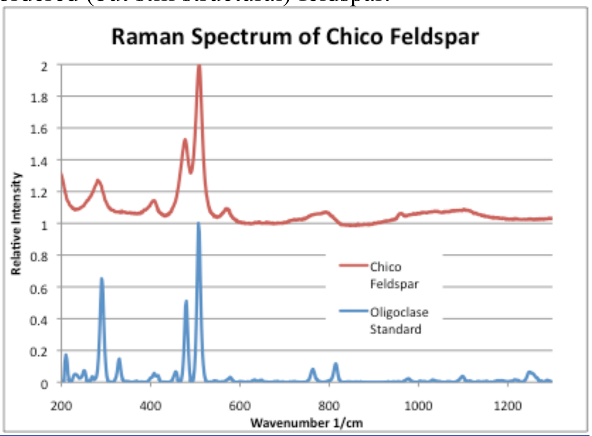

Figure 1. Raman spectra of Chico feldspar and oligoclase standard.

Ar diffusion: The total K concentration in the two splits of Chico is ~540 and ~640 ppm. A high temperature resolution Arrhenius plot shows the host material from the Chico meteorite actually contains three or four domains, two below 1000 °C, and one or two above 1000 °C. ^{39}Ar and ^{37}Ar give the same result, indicating the phase associations of K and Ca are the same. The 1st low T release (containing ~3-5% of the ^{39}Ar) has E = 25 ± 5 kcal/mol, the same as seen in the shocked albite that was converted to glass. The 2nd low T release (~55-60% of the ^{39}Ar) has E = 51 ± 5 kcal/mol, within error of the 46 ± 3 kcal/mol found in unshocked albite. The high T release (~30-40% of the ^{39}Ar) has E = 136 ± 7 kcal/mol, in the 80-131 kcal/mol range measured in pyroxene. A second high T release is hard to confirm or measure due to low temperature resolution and the variability of duplicate steps, but is a possibility.

NWA 091 gives similar results to Chico, but it only contains a single release below 1000 °C (~35-40% of the ^{39}Ar) with E = 27 ± 6 kcal/mol, again the same as shocked albite. The high T release (~55-65% of the ^{39}Ar) has E = 117 ± 11 kcal/mol, also consistent with pyroxene.

Olivine has an E close to that of unshocked feldspar, but remains a high T mineral due to a low frequency factor. Neither meteorite has an obvious presence of olivine in the Arrhenius plot, though olivine would be a likely choice for a second high T release.

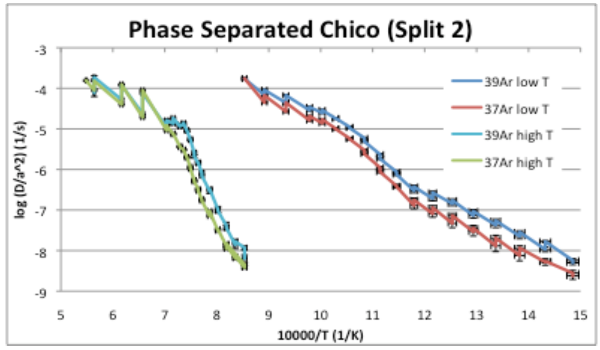

Figure 2. Arrhenius plot for Chico.

Conclusions: The K mass balance of Chico shows that virtually all the K in the meteorite is contained in the feldspar, and microprobe and ^{39}Ar-based results are consistent. Raman spectroscopy of the feldspar in Chico shows that it is disordered (but still structural) feldspar, though a very small amount of glass could have escaped detection. This is consistent with the Ar diffusion measurements, which show ~5% of the ^{39}Ar has an E matching shocked feldspar, and ~60% of the ^{39}Ar has an E matching structural feldspar. The remaining ^{39}Ar has an E similar to pyroxene. Since all the K is contained in feldspar, it would appear the remaining K is contained in feldspar that is fully enclosed in pyroxene, and hence forced to outgas along with the pyroxene. The thin section does indeed show feldspar enclosed by pyroxene (at least in two dimensions), but preliminary results indicate that more feldspar is enclosed by olivine. Weirich et al. (2011) [7] showed that NWA 091 has two high T releases in the age spectrum, so enclosure by both pyroxene and olivine is possible. The diffusion parameters of NWA 091 give a similar story as Chico, though in this case shock has converted all feldspar to maskelynite.

It is unclear whether the high T release can be used to perform Ar thermochronology on meteorites, because the release of gas from inclusions violates the assumptions that are used to convert bulk-release data into diffusion parameters. The low T release (feldspar) can be used for thermochronology as long as the structural state of the feldspar is known, and proper phase separation can be performed.

References: [1] Bogard D. D. and Hirsch W. C. (1980) *GCA, 44,* 1667-1682. [2] McCoy et al. (1995) *GCA, 61,* 623-637. [3] Weirich J. R. et al. (2010) *LPS XLI,* Abstract # 2137. [4] Bogard D. D. et al. (1995) *GCA, 59,* 1383-1399. [5] Grossman J. N. and Zipfel J. (2001) *MAPS, 36,* A293-A322. [6] Lovera O. M. (1997) *GCA, 61,* 3171-3192. [7] Weirich J. R. et al. (2011) *LPS XLII* , submitted.