CHELYABINSK AR AGES – A YOUNG HETEROGENEOUS LL5 CHONDRITE. F. N. Lindsay[1], G. F. Herzog[1], J. Park[1, 2, 3], B. D. Turrin[4], J. S. Delaney[1], and C. C. Swisher, III[4], [1]Rutgers University, Dept. of Chem & Chem. Biol., 610 Taylor Rd, Piscataway, NJ 08845, USA (flindsay@rci.rutgers.edu), [2]Lunar Planet. Inst., Houston, TX 77058, USA. [3]Kingsborough Comm. Coll. (CUNY), Brooklyn, NY 11235, USA, [4]Rutgers University, Earth & Plant. Sci., 610 Taylor Rd, Piscataway, NJ 08845, USA.

Introduction: The Chelyabinsk fall provides a unique opportunity to examine the connection between sample heterogeneity and impact history of a meteorite. [1] and [2] reported Ar/Ar systematics for 2 and 1 Chelyabinsk bulk rock samples, respectively, which show disturbances between 28 – 3500 Ma. Re-setting of the radiochronometers has also been seen in the Sm-Nd and Rb-Sr systems (290 Ma; [3]). We apply the petrologically sensitive ^{40}Ar-^{39}Ar chronometer to smaller-sized samples in order to examine the interaction of sample heterogeneity with the chronology of the meteorite and its parent asteroid. We present measurements for 11 samples from 6 fragments.

Samples: We received six different chips of the Chelyabinsk meteorite from 2 sources: 1) Johnson Space Center (Kevin Righter, JSC) and 2) University of New Mexico (Rhian Jones, UNM). From JSC we obtained 4 chips: 101-7, 101-15, 102-7 and 103-6. The 101 samples contain both unshocked silicate clastic lithology and small volumes of melt veins and pockets. The latter two samples are predominantly impact melt material [4]. From UNM we acquired 2 chips. Clast 001h, which is mostly light clastic lithology, has a thin layer of impact melt on one surface that does not appear on the opposite side of the fragment. Stone 020 is an impact melt fragment that has no visible fusion crust.

Procedures: Plagioclase grains were separated from silicate clastic-rich samples (JSC 101-7, JSC 101-15, UNM 001h) using heavy liquid density separation techniques (ρ=2.85 g/cm^3, T=25 °C) after gentle crushing. Bulk samples (masses between 225 and 575 µg) of each of the 6 fragments received were also chosen for Ar isotope measurements. Backscatter imaging and energy-dispersive spectroscopy (EDS) were used to characterize predominantly mono-mineralic mineral grains.

The Chelyabinsk grains were co-irradiated with the reference mineral Fish Canyon sanidine (FC-2) to calibrate the neutron fluence. The age adopted for FC-2 is 28.201 Ma [5]. Decay constants are from [6] and reactor constants are from [7].

Each sample was heated to fusion using 6 to 14 heating steps. Argon isotopes were analyzed [8] with typical system blanks (laser off) of (10^{-18} mol): ^{40}Ar =272±6; ^{39}Ar=7.6±0.6; ^{38}Ar=2.3±0.3; ^{37}Ar=36±0.4; ^{36}Ar=6.7±0.3. Uncertainties are expressed as 1σ unless otherwise specified.

Results:

Integrated Ages: Integrated ages of the samples range from 264±2 Ma to 2083±5 Ma (Table 1). Our ages fall within the wider range of step ages reported by [1] (28 to 3500 Ma).

Plateau Ages: Four plagioclase separates give apparent plateau ages; seven other measurements do not form plateaus (fig 1). The spectra with the most ^{39}Ar gas released in the plateaus, 100% and 82%, have ages of 1184±40 Ma and 730±32 Ma, respectively. The other two apparent plateau ages, 1014±24 Ma and 312±6 Ma, include 51% and 60% cumulative ^{39}Ar gas, respectively, released during the low and intermediate temperature steps.

Release Patterns: The release patterns are similar in shape to that reported by [2]. The majority of the release spectra, for both plagioclase separates and bulk samples, have a rising stair-step pattern, although a few have a shallow saddle pattern, in which the lower to intermediate temperatures have the youngest apparent ages. The stair-step patterns of the age spectra reflect heterochemical phases within the samples [9] – particularly bulk samples. The few high temperature steps with higher ages in the separated plagioclase samples may reflect incomplete separation of phases, i.e., a remnant of a different phase may be adhered to the grain.

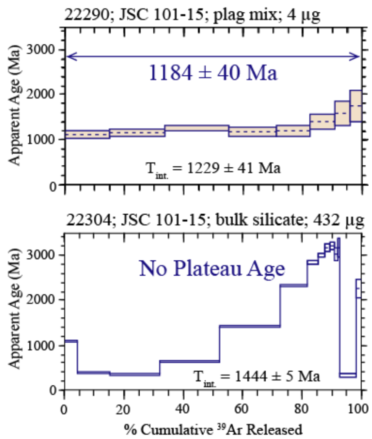
The clastic-rich bulk samples typically show low apparent ages for 60% - 80% of the gas released before increasing in the high temperature steps to ≤ 3200 Ma. A few show a somewhat higher first temperature step, likely reflecting atmospheric contamination on the sample's surface. We observed ages above 3000 Ma in only two samples: a clastic-rich bulk sample (22304; JSC 101-15) released ~ 6% of its gas at an apparent age of ~ 3200 Ma; a plagioclase separate 22292 (JSC 101-7) released ~ 2% of its gas in a high temperature step at ~ 3500 Ma.

The release patterns of the melt-rich and clastic-rich samples are similar. They differ in that the melt-rich samples release a greater percent of gas at high temperatures than the clastic-rich samples. These high temperature steps dominate the integrated ages, causing the the melt samples to be among the oldest (> 1400Ma).

The integrated age of the bulk UNM impact melt is older than the UNM clastic fragment by ~ 2 Ga, similar to a trend noted by [1]. The data for JSC samples, however, are more ambiguous; the bulk melt samples have integrated ages (852 and 1464 Ma) that span the ages of both plagioclase separates and clastic bulk samples.

^{40}Ar loss: If we assume that the parent body of Chelyabinsk formed at 4.5 Ga, our samples have lost between 92% and 99% of ^{40}Ar*, consistent with measurements by Nagao[10]. Overall, the fraction of 40Ar* lost does not vary much despite the variation in apparent and integrated ages. There is a ~2× difference in the integrated ages of plagioclase separated from the JSC 101-7 fragment (22291 and 22292) and in the plateau ages of UNM 001h (22293 and 22296); integrated ages differ ~8× across all samples.

Figure 1. Release diagrams of our "best" plagioclase separate and our "worst" bulk sample. Uncertainties are 1σ.



Discussion: The ages of 22296 and 22322 (Table 1) show evidence of heating ~300 Ma. Such recent events have also been seen in the Sm-Nd and Rb-Sr systems (290 Ma; [3]). We see some evidence for a disturbance at 100 Ma (22322) not at 28 Ma as [1] report, but note that we sampled different fragments of the very heterogeneous Chelyabinsk [1, 4, 11-14]. With such a variety of apparent ages it is difficult to say more than that Chelyabinsk was massively disturbed within the last 300 Ma. ^{40}Ar losses, demonstrated for several different samples, imply that gas loss was both widespread and chaotic on a spatial scale of less than 1 mm. A large collisional event would seem the obvious explanation, although low-velocity collisions among small asteroids are not expected to induce large-scale gas losses [15,16].

[1] show that ages for a melt-rich sample are older than ages for clastic-rich sample and propose an event in which the clastic-rich fragments were more thoroughly degassed (~30 Ma). Analogous results were reported for Peace River (L6) by [17] who proposed that Ar may have had to diffuse along a longer path in newly formed glass than in nearby, unmelted crystals. While this sequence of events is plausible, it is not the only possible outcome in the aftermath of glass-making and indeed, our observations for Chelyabinsk show no uniform relation between the apparent ages of the glass and the bulk rocks. Other scenarios in which impact melts might show older ages than clastic fragments are also possible.

First, the melt may incorporate and homogenize older relict grains and/or chondrules giving an age that is a mixture of old ages and a younger event.

Second, the event that reset a clastic fragment may have affected the impact melt to a different degree. There is no requirement that the glass and clastic material were proximal at the time of impact. The possibility that the two fragments were distal and experienced the same event differently is equally plausible.

Third, the parent body may have been battered at different times (and in different locations) throughout its history with Chelyabinsk eventually splitting from that parent body, leaving a record of age variations consistent with those reported (between 28 [1] and 4538.3 [18]).

Table1. Plateau and Integrated ages of measured samples.

Sample	Run ID	mass µg	Integrated Age Ma	Plateau Age Ma
plag mix 101-15 (light); JSC	22290	4	1229±41	1184±40
plag mix 101-7 (dark); JSC	22291	7	775±11	
plag 101-7 (dark); JSC	22292	3.5	1316±18	1014±24
plag 001h; UNM	22293	2	941±33	730±32
impact melt; JSC	22294	276	852±10	
impact melt; JSC	22295	476	1464±11	
plag mix 001h; UNM	22296	22	392±06	312±06
bulk 101-7 (dark); JSC	22303	341	1112±11	
bulk 101-15 (light); JSC	22304	432	1444±05	
melt 020; UNM	22320	573	2083±05	
bulk 001h; UNM	22322	232	264±02	

Without petrologic constraints, however, it is difficult to interpret the age relations. Further work is needed before assigning events or a single impact to the variation seen in the Chelyabinsk Ar-Ar ages.

Conclusions: The varied Ar-Ar ages of the LL5 chondrite Chelyabinsk reflect the lithological and impact heterogeneity of different fragments of the meteorite. A clearer understanding of these thermal events will emerge as the relationship of the fragments to each other and to the parent meteoroid are better integrated.

References: [1] Beard S.P. et al. (2014) *LPS XLV*, #1807 [2] Haba M.K. et al. (2014) *LPS XLV*, #1732 [3] Galimov E.M. et al. (2013) *Geokhimiya* **51**:580–598. [4] Righter et al. (2015) *this conf.* [5] Kuiper K.F. (2008) *Sci.* **320**:500-504. [6] Steiger R.H. and Jäger E. (1977) *EPSL* **36**:359-362. [7] Dalrymple G.B. et al. (1993) *USGS Bull.* [8] Turrin B.D. et al. (2010) *Geochem. Geophys. Geosyst.* **11**. [9] Chafe A.N. et al. (2014) *Contrib Min Petrol* **167**:1010. [10] Park, J. (2015) *this conf.* [11] Kohut T. et al. (2014) *Icarus* **228**:78-85. [12] Popova, O.P. et al. (2013) *Sci.* **342**:1069-1073 [13] Kring D.A. et al. (2013) *MetSoc* #5224. [14] Bischoff, A. et al. (2013) *MetSoc* #5171. [15] Keil, K. et al. (1997) *MaPS* **32**:349-363. [16] Marchi S. (2013) *Nature Geosci.* **6**:303-307. [17] McConville, P. (1988) *GCA* **52**:2487-2499. [18] Bouvier, A. (2013) *Large Meteorite Impacts & Planetary Evolution V*, #3087.