AR-AR STUDIES OF DHOFAR CLAST-RICH FELDSPATHIC HIGHLAND METEORITES: 025, 026, 280, 303. V. A. Fernandes[1,2] (veraafernandes@yahoo.com), M. Anand[3], R. Burgess[2], and L. A. Taylor[3]. [1]Inst. Geofísico, Univ. Coimbra, Portugal; [2]Dept. Earth Sciences, University of Manchester, UK; [3]Planetary Geosciences Institute, Univ. of Tennessee, KnoxvileUSA.

Impact Flux through time

A prominent feature of the lunar surface is its scarred surface. This feature is the result of bombardment of the Moon by objects of varying sizes after its formation. The region most affected, or that which shows a higher density of craters formed by these events, are the highlands (lunar anorthositic crust), with the maria showing comparatively lower density. This impact density contrast suggests that highlands are older than the less cratered maria surfaces. An important debate in lunar science is understanding the significance of the dominant impact age of ~3.9 Ga obtained from lunar highland rocks collected by Apollo and Luna missions, in relation to changes in the impact flux. Was it due to a cataclysmic event at 3.9 Ga [1-5] which formed several of the largest basins in the lunar nearside (Imbrium, Crisium and Serenitatis) or was it due to a continuous decrease in the flux of impacting material in the vicinity of the Earth-Moon system since the beginning of the accretionary period (the heavy early lunar bombardment) that ended ~3.9 Ga [6-7]? The aim of the present work is to acquire cooling ages from impact melts within feldspathic regolith lunar meteorites, to not only increase the number of such ages, but also to extend the geographical coverage of lunar highland rocks over the lunar surface.

Experimental methods. Impact-melt clasts within four lunar meteorites found in Oman: Dhofar 025 (Dho 025, an anorthositic regolith breccia meteorite [8]; Dhofar 026 (Dho 026, a clast-poor, anorthositic, crystalline melt breccia meteorite [9]; Dhofar 280 (Dho 280, a lunar fragmental breccia meteorite [10]; and Dhofar 303 (Dho 303], a lunar conglomerate impact melt breccia meteorite [11]) were distinguished on the basis of chemical composition using EMPA at the Univ. of Tennessee. Impact ages are being obtained using laser Ar-Ar dating experiments at the Univ. of Manchester: (1) UV laser spot (5 μm) fusion of a polished thick section of meteorite (the small size of the beam permits the targeting of individual minerals within the different clasts, increasing the spatial resolution of ages within the meteorites; and (2) IR laser in-situ stepped heating of an area of individual impact clasts within Dho 280 and Dho 303. IR-laser step-heating permits to obtain the primary age of a sample, and/or the age of other events after formation (e.g. identification of any loss of Ar: the ^{40}Ar measured will be that which accumulated since the event, thus an age for the event can be determined). Also, from the plot produced with the data acquired, it is possible to identify different argon components within the sample (e.g. cosmogenic, radiogenic, trapped). Preliminary results from experiments (1) and (2) are presented here.

UV- laser spot analyses: This technique was used on the four meteorites studied and a summary of the results is reported below and in Table 1.

Dho 025 In the studied thick section of this meteorite, 25 different clasts were identified that showed varied, low K content and high excess ^{40}Ar. Preliminary UV-laser spot analyses of 4 clasts have been obtained. From each clast 2-7 spots were obtained, the number being dependent on the size of the clast. In most cases, the ages obtained were greater than that of the solar system (i.e. >4.5 Ga). Ages ranged from 3.31$\pm$0.24 (Clast I) to 6.80$\pm$0.61 Ga (Clast A). The youngest age was obtained from Clast I from which a total of 4 spots were ablated each giving a different age. A wide range of cosmic ray exposure (CRE) ages was obtained [22.1$\pm$8.6 (Clast I) – 131.1$\pm$7.6 Ma (Clast A)].

Dho 026 The thick section of this meteorite is dominated by a single lithology referred to as "matrix" (classified as a crystalline impact melt by [8]) within which five clasts were identified. K concentrations of the clasts were low, 200-500 ppm, and highly variable both within and between different clasts. Combined with the low K concentration was the presence of trapped Ar components derived from the lunar atmosphere and solar wind implantation. The trapped components have a high ^{40}Ar/^{36}Ar$_t$ value of 100-1136. UV-spot analyses were carried out on two clasts and "matrix" (K varied from ~270 to ~1170 ppm). The results show a wide range of apparent ages within each clast – caused by the dominance of trapped ^{40}Ar component. Seven UV-laser spots were made on Clast A; the age range is 2.16$\pm$0.21 - 5.07$\pm$1.71 Ga. Three spots were obtained on Clast E giving an age range between 1.56$\pm$0.16 - 3.94$\pm$0.60 Ga. Of the seven UV-laser analyses of the matrix only five released sufficient K-derived ^{39}Ar to yield apparent ages of 2.16$\pm$0.42 – 6.81$\pm$0.32 Ga. The minimum ages obtained for Clasts A and E (2.16 and 1.56 Ga) are considered as maximum ages for the impact event that formed these clasts. From all the 17 spots acquired on this thick section, only one, within the "matrix" gave a reasonable CRE age of 10.9$\pm$ 2.2 Ma (the same as that determined by [12], as most of the samples contained little ^{38}Ar to be detected above background. Low cosmogenic ^{38}Ar in this meteorite had already been reported by [13] and is suggested to be due to the short transfer time between Moon-Earth of 10^4 years.

Dho 280 A Total of 28 UV-laser spot analyses from 8 clasts within this thick section were obtained. Most of the clasts showed very low to almost negligible K content, high trapped ^{40}Ar of possible parentless origin including that integrated in the melt upon the impact event. The ^{40}Ar has no relation to the K within the sample, thus in most cases, the age obtained was older than the solar system. The only reasonable ages obtained were 2.33$\pm$0.41 and 2.77$\pm$0.61 Ga in Clast C, and 3.33$\pm$0.75 and 3.72$\pm$0.32 from plagioclase fragments included in the "matrix". These ages can be thought of as ages for different impact events that may have disturbed the plagioclase fragments. Most of the ^{38}Ar/^{36}Ar content in the impact melt clasts of this sample is a mixture of trapped (~0.19) and cosmogenic (1.54). The CRE-age range is 46 – 686 Ma. The older ages acquired are, on the other hand, related to $^{38}Ar/^{36}Ar$ with a value close to trapped value of 0.1869.

Dho 303 Seven clasts within this thick section were identified and UV-laser spot analyses were performed on all of them (a total of 21). These clasts contained very low K contents (<200 ppm) and relatively high levels of trapped ^{40}Ar, again possibly incorporated in the clast during the impact event. The trapped ^{40}Ar released overwhelms the radiogenic and has no relation to the K within the sample, and the apparent ages obtained are all much greater than 4.5 Ga except for a single age of 3.62±0.20 Ga. The content of ^{36}Ar is very low to non-existent in some cases after blank and cosmogenic correction, reinforcing the idea that the high ^{40}Ar content within these impact clasts is likely to be retrapped Ar. The CRE ages obtained are older than that of Dho 026, having an age range of 22-128 Ma. it has been suggested [14] that hot desert meteorites adsorb atmospheric noble gases ($^{40}Ar/^{36}Ar$=295.5). Using this value for correction of $^{40}Ar/^{36}Ar_t$, the over correction for ^{40}Ar is lessened, showing the variability of ages obtained from each Clast. The ages obtained are: 2.44±0.30 and 4.19±0.25 Ga (a plagioclase) for Clast A; 4.09±0.46 for Clast B; 4.42±0.05 and 4.27±0.27 Ga for Clast D; and 3.68±0.20 and 3.61±0.34 Ga (both from plagioclases) for Clast E.

IR-laser in-situ stepped-heating: Because of the difficulties in resolving radiogenic ^{40}Ar from the UV laser experiments, in-situ IR-laser step heating analyses were made on Clast C from Dho280 and Clast F from Dho 303. A summary of the results is reported below.

Dho 280 In-situ step heating of Clast C showed that the ^{39}Ar measured after an extraction had values slightly above background suggesting the non-existence of sufficient K within the sample to make it possible for an age to be determined. The total age obtained is 6.52±1.10 Ga. The total CRE-age obtained has a value of 22.3±1.2 Ma, similar to the high temperature steps comprising 41% of the total ^{37}Ar release.

Dho 303 The initial results for the IR-laser in-situ stepped heating on Clast F show for some steps at low temperatures

an age range from 0.73-1.3 Ga; the higher temperature steps show the release of trapped ^{40}Ar and negligible ^{39}Ar, and the ages do not have any geological meaning. The total $^{40}Ar/^{39}Ar$ age obtained for this clast is 7.80±2.37 Ga, and total CRE-age is 886±30 Ma (higher than any age obtained in the UV-laser spots).

Summary: In the present study of Ar-Ar systematics of feldspathic clasts in 4 lunar regolith breccias, crystallization ages of these clasts were not obtained with some exceptions, most being of plagioclase fragments. The main reason is the ^{40}Ar present within the clasts is mostly excess Ar, all volume correlated, but much of it obscuring the radiogenic ^{40}Ar and has no relation to the potassium within these clasts. Thus, step heating (or etching) is not helpful. It has, however, become clearer the origin and processes by which ^{40}Ar was trapped within the clasts of Dho 025, Dho 026, Dho 280 and Dho 303. The most likely process was the retrapping of pre-existing radiogenic ^{40}Ar during impact, or of atmospheric Ar, combined with significant K loss, as in most cases was not detectable (about the blank value). Few ages were obtained and are younger than 3.9 Ga. Similar difficulties in age determination of impact-melts within Dho025 and Dho 026 had previously been reported by Cohen et al (2002) CRE-ages obtained are within those determined for lunar regolith and each meteorite shows a wide range of CRE-ages. This result is not surprising considering the nature of the meteorites being impact-melt rich feldspathic regolith breccias.

. The UV-laser spot analysis previously used by [15] in combination with step heating was shown to be an important complementary methods to acquire detailed data from within a lunar breccia meteorite. However, the Ar systematics within these Dhofar samples appear too enigmatic to be deconvolved presently.

Refs: [1] Turner et al. (1973) LPSC IV, 1889-1914. [2] Tera et al. (1974) EPSL, 22, 1-21. [3] Bogard (1995) Meteor., 30, 244-268. [4] Dalrymple and Ryder (1993) JGR. 98, E7, 13,085-13,095. [5] Dalrymple and Ryder (1996) J.GR, 101, E11, 26,069-26,084. [6] Wetherill (1981) XII, 1-18. [7] Culler et al. (2000) Science, 287, 1785-1788. [8] Cohen et al (2001), LPSC XXXII, abst.#1840. [9] Cohen et al. (2001) LPSC XXXII, abst#1404. [10] Anand et al (2002), LPSC XXXIII, abst#1653. [11] Nazarov et al (2002), LPSC XXXIII, abst#1293 [12] Shukolyukov et al. (2001), LPSC XXXII, abst#1502. [13] Nishiizumi et al. (2001), MetSoc 64th, abst.#5411. [14] Scherer et al. (1994), In: Noble Gas Geochemistry and Cosmochemistry, 43-53. [15] Fernandes, et al. (2000) Meteor. & Plan. Sci., 35, 1355-1364. [16] Cohen at al. (2002), LPSC XXXIII, abst.#1252.

Table 1 Representative results from Dho 025 (Clast I) and Dho 026 (Clast A Dho 280 (Clast C) and Dho 303 (Clast E). nd not determined due either to low K content or low ^{36}Ar, which was lower than the background value.

	Age (Ga)	$^{40}Ar/^{36}Ar_t$	CRE Age(Ma)	$^{38}Ar/^{36}Ar$		Age (Ga)	$^{40}Ar/^{36}Ar_t$	CRE Age(Ma)	$^{38}Ar/^{36}Ar$
Dhofar 025					Dhofar 280				
Clast I shot 1	3.31±0.24	9.65±0.29	55±7	0.22±0.01	Clast C shot 1	2.33±0.41	75.95±2.86	94±7	0.74±0.03
Clast I shot 2	nd	37.81±2.05	31±5	0.42±0.03	Clast C shot 2	4.40±0.32	259.59±10.14	112±6	0.84±0.04
Clast I shot 3	5.48±0.89	372.62±14.49	42±6	0.61±0.04	Clast C shot 3	5.14±2.26	354.30±37.42	110±8	1.19±0.10
Clast I shot 4	8.92±10.25	38.42±0.95	34±11	0.24±0.01	Clast C shot 4	13.63±32.02	394.57±22.72	109±3	1.26±0.08
Dhofar 026					Clast C shot 5	2.77±0.61	484.93±79.04	89±8	1.26±0.15
Clast A shot 1	2.61±0.30	279.11±18.14	5±3	0.30±0.06	Clast C shot 5	7.22±1.05	353.22±3.40	85±2	1.02±0.02
Clast A shot 2	1.61±0.28	374.52±45.46	5±3	0.50±0.19	Dhofar 303				
Clast A shot 3	2.16±0.21	580.54±120.51	5±3	0.41±0.17	Clast E shot1(plag)	3.62±0.20	nd	22±2	1.59±0.19
Clast A shot 4	4.29±1.43	nd	nd	nd	Clast E shot 2	8.36±5.85	447.83±53.13	11 ±2	0.52±0.06
Clast A shot 6	nd	nd	5±6	0.02±0.13	Clast Eshot3(plag)	4.69±0.35	742.77±32.97	24±2	0.93±0.05
Clast A shot 7	5.07±1.75	nd	nd	2.32±8.02					
Clast A shot 8	5.74±18.11	nd	nd	0.80±0.63					