СЛИВА ИЗ ПИРОГА : K/Ar EVIDENCE FROM LUNA 20 ROCKS FOR LUNAR DIFFERENTIATION PRIOR TO 4.51 AE AGO. J. C. Huneke and G. J. Wasserburg, The Lunatic Asylum, Division of Geological and Planetary Sciences, Caltech, Pasadena, CA 91125

^{40}Ar-^{39}Ar ages have been measured on a basaltic rock 22012 from the 14-23 cm depth interval of the Luna 20 core and an anorthositic rock 22013 from the 32-41 cm depth interval, as part of a consortium study on these fragments including petrographic and mineralogical characterization [1] and INAA elemental analysis [2]. The fragments were included in the LAC 1 neutron irradiation [3]. All K/Ar ages are calculated using the newly recommended values for ^{40}K isotopic abundance and decay parameters [4].

22012 is a fine-grained basalt comprised of plagioclase, pyroxene, olivine, and abundant K-rich mesostasis in an intergranular to intersertal texture suggesting rapid crystallization from a melt [1]. 22012 is chemically and texturally similar to other medium-K feldspathic highland basalts [1,2]. The age spectrum (fig. 1) begins with very young ages correlated with high K/Ca, reflecting low temperature losses from the K-rich mesostasis. The ages increase with ^{39}Ar release to a maximum at 4.08 AE, decrease anomalously to a minimum and increase again to 4.3 AE. The minimum in $^{40}Ar/^{39}Ar$ corresponds to a maximum in spallation $^{38}Ar/^{37}Ar$, suggesting the correlated release of recoil implanted ^{39}Ar and spallation ^{38}Ar from mafic minerals depleted in Ca-derived ^{37}Ar [5]. If 22012 crystallized rapidly from an impact melt [1], the highest temperature release may reflect incomplete degassing or include contributions from relict material. 22012 material was last totally degassed more than 4.2 AE ago and may have been extensively degassed in the interval 4.1-4.2 AE. Significant low temperature losses have occurred since 3.2 AE ago.

22013 consists of white, totally shock metamorphosed plagioclase with polygonal aggregates of mafic minerals along grain boundaries. Plagioclase is predominently recrystallized with partially isotropic patches. 22013 contains a layer of dark gray recrystallized plagioclase with a vesicular aggregate of mafic minerals. The rock is chemically similar to ferroan anorthosites in mafic mineral composition, but to ANT-suite rocks in plagioclase composition. K and REE contents are similar to those in high K anorthosites. The dark (9001) and white (9002) lithologies were both sampled for INAA and K/Ar studies. The age spectra are shown in figs. 2 and 3. Ar released over the same temperature intervals is labeled by the same numeral. The age patterns are very similar over regions I-III. Ages are initially low and increase rapidly to well-defined age plateaux at 4.17 AE over region I. The ages then increase to reasonably well-defined high temperature age plateaux at 4.36 AE over regions II-III. In contrast to 9001, the age spectrum of 9002 then increases at the highest temperatures (region IV) to yet another age plateau at 4.51 AE containing over 50% of the Ar released. K/Ca for both fragments is constant over the Ar release comprising the age plateaux. The K/Ar ages determined from the total Ar release are 4.26 AE (9001) and 4.41 AE (9002). The ages on 22013, 9002 are the oldest Ar retention ages so far reported for lunar samples and establish this rock type as an early lunar differentiate. Ages of 4.39 AE reported for the high temperature Ar release from breccia 65015 [6] and 4.36 AE for a plagioclase clast from breccia 67435 [7] were the oldest K/Ar ages for lunar rocks previously reported. The intermediate plateau ages achieved by 22013 are comparable to these ages.

A hint of the existence of ancient materials at the Luna 20 site was presented in the work of Turner and Cadogan [5] on a sample of mixed anorthositic fragments. The result of ^{40}Ar-^{39}Ar dating of this sample was ambiguous due to

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large required corrections for trapped ^{40}Ar accompanied by ^{36}Ar. With restrictive assumptions about trapped Ar composition, an age of 4.3±0.1 AE was inferred, and it was concluded that in any case the data demonstrated the presence at the Luna 20 site of older material not degassed in the cataclysm at ~ 3.9 AE. 9001 and 9002 both contain devitrified material but differ by the presence of undevitrified patches of plagioclase composition in the latter. The 4.51 AE age presumably can be associated with undevitrified material. The age spectra in regions I-III and the plateaux at 4.17A and 4.36 AE would seem to be associated with the recrystallized plagioclase. The assumption above that undevitrified shock glasses behaved as closed systems during shock metamorphism is not fully resolved, nor is devitrification well correlated with gas loss.

It is important to address the issue of whether or not trapped ^{40}Ar not arising from in situ decay of ^{40}K is present. The presence of trapped ^{36}Ar would be a clear indicator for the possible presence of trapped ^{40}Ar, but ^{36}Ar in 22013 is entirely spallogenic. It is conceivable that trapping of pure ^{40}Ar could occur. The surest evidence for this would be the existence of K/Ar ages greatly in excess of 4.6 AE. A large number of ages greater than 4.0 AE have now been reported including several ~ 4.4 AE, but only one, on an olivine mineral separate from 76535 [8], has been greater than 4.6 AE. The paucity of ages > 4.6 AE makes it increasingly unlikely that inclusion of trapped ^{40}Ar

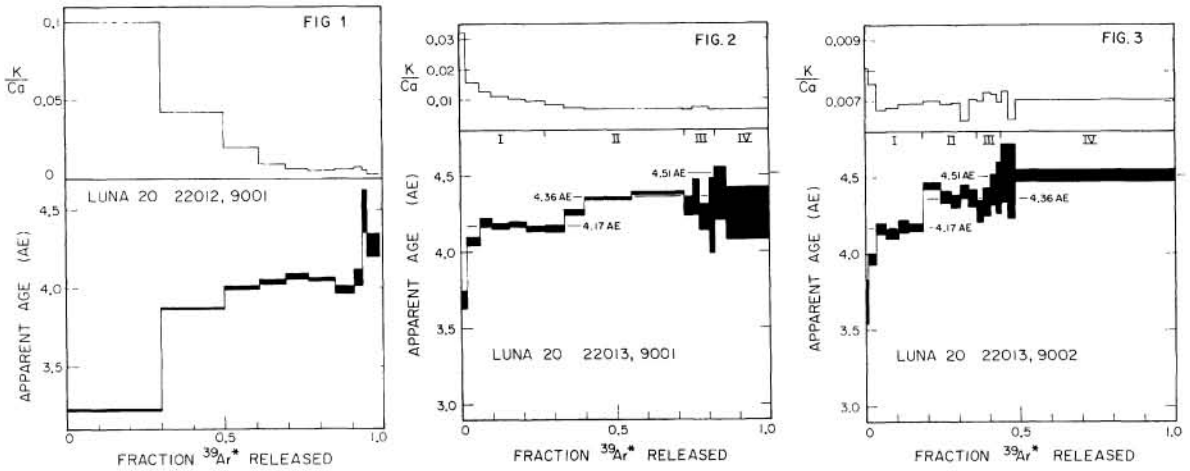

Fig. 1. Apparent age and K/Ca vs ^{39}Ar release from a fragment (5.5 mg) of the Luna 20 highland basalt 22012. The ages are initially young, increase to a maximum at 4.1 AE, decrease anomalously, and increase again to 4.3 AE. An age plateau is not well developed. There is significant low temperature ^{40}Ar loss from high K/Ca mesostasis. The decrease due to release of recoil implanted ^{39}Ar from mafic minerals masks the plateau region. 22012 formed ≥ 4.2 AE ago and may have been extensively degassed 4.1-4.2 AE ago.
Figs. 2 and 3. Apparent age and K/Ca vs ^{39}Ar release from fragments 9001 (7.1 mg) and 9002 (6.4 mg) of the heavily shocked Luna 20 anorthositic rock 22013. Numerals identify Ar extracted over the same temperature intervals. The age spectra are the same cver I-III. Ages increase rapidly to well defined plateaux at 4.17 AE (I) and then again to 4.36 AE (II,III). The 9002 spectrum increases to yet another plateau at 4.51 AE. K/Ca is constant over the plateaux. 22013 formed ≥ 4.51 AE ago and is one of the oldest lunar rocks identified. It was severely degassed 4.36 AE ago and again 4.17 AE ago, but unaffected by the 3.9 AE terminal lunar cataclysm.

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without trapped ^{36}Ar is a common mechanism. We conclude that the old ages measured here are reliable indicators of time.

The age spectra presented here do not show any gross evidence of pathological behavior, although fine structure does exist. The 22013 age spectra are generally increasing, and the spectra are amenable to the traditional explanation that material releasing Ar at progressively higher temperatures has been increasingly resistant to degassing in the lunar environment. The oldest ages may reflect redistribution of Ar in the ^{40}Ar-^{39}Ar experiment, but even so, the total K/Ar age of 4.41 AE still establishes 22013 as one of the oldest of lunar rocks.

The K/Ar age of 22013, 9002 is comparable to the Rb-Sr ages measured for the dunite 72417 [9] and troctolite 76535 [10]. Those ages provide the best determination for the time of early lunar differentiation. The K/Ar age for 22013 of $\geq$ 4.51 AE provides an important confirmation for large scale differentiation prior to 4.51 AE resulting in anorthositic rocks as well as troctolites of the ANT suite and dunites. 22013 cannot be an old rock buried at great depths in the moon and excavated at 3.9 AE, since the temperature at great depths should have been sufficient to prevent ^{40}Ar accumulation until the time of excavation. This may have been the case until 4.51 AE ago, but since then 22013 has resided at shallower depths insufficient to completely degass the fragment. 22013 has also not been seriously degassed by impact heating since 4.4 AE, despite its existence close to the lunar surface during intensive planetesimal bombardment.

The 22013 age of 4.17 AE dates relatively mild degassing or excavation from a depth in the moon insufficiently hot to cause losses of ^{40}Ar from the more retentive material (regions II-IV) over the time interval 4.4-4.2 AE. The age of 22012 of $\geqslant$ 4.2 AE dates a time extensive degassing or excavation from a depth sufficient to totally degass 22012 material prior to excavation. The age may also date crystallization of 22012 from an impact melt. Turner and Cadogan [5] and Maurer et al. [11] note the occurrence of a number of well-defined ages for A16 and A17 rocks clustering about ~ 3.9 and ~ 4.15. The ages so far obtained on Luna 20 samples support this clustering, with two ages 4.1-4.2 AE and from previous measurements on 22006 and 22007 [12] two ages at 3.84 AE. The two age clusters may reflect only two large impact events or two episodes of intensive cratering by large bodies excavating the moon to great depths. We argued previously from the large distances between sampled sites and the ubiquitous occurrence of ~ 3.9 AE ages that the event(s) resetting ages to that time affected the whole moon [12]. Similarly, we can conclude the 4.17 AE event(s) has also left an imprint over large areas of the moon's surface. The wide geographic distribution of both age clusters suggests each episode was a multiple event. In particular, the ~ 4.15 AE cratering was evidently too shallow to penetrate to KREEP rich layers [11] and the coverage of the ejecta of a single 4.15 AE event would be much more limited in extent and depth than for the Imbrium event. Compared to other sampled sites, a remarkably large fraction of samples from Luna 20 have retained clear evidence of early origins, which suggests that evidence of earlier lunar history becomes more accessible further away from the center of late basin-forming activity on the lunar frontside, and that the best documentation of early lunar differentiation history would be obtained from lunar backside samples.

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