Noble-Gas Isotope Systematics of Lunar Anorthosites: Hunting For Indigenous Signatures J. F. Pernet-Fisher* and K. H. Joy. School of Earth and Environmental Sciences, University of Manchester, M13 9PL, UK (*john.pernet-fisher@manchester.ac.uk).

Introduction: Noble gases, while chemically inert, are important tracers of physical processes across the Solar System [1-4]. For lunar samples they can be used for: constraining lunar degassing (He, 36,40Ar); provide an archive of solar history (40Ar, 129Xe, 131-138Xe); constrain surface exposure ages (e.g., 21Ne, 39Ar); and can be used to date samples using in-situ produced radiogenic isotopes (40Ar) [4].

Here we present the noble-gas (Ar, Kr, Xe) isotope systematics of a suite of 10 Apollo highland anorthosites in order to investigate the physical history of these samples. Over the last few years there has been a renewed interest in investigating highland anorthosites [5-8]. The anorthosite suite are an important lithology as they represent the crystallisation products of the lunar magma ocean (LMO), thus, understanding the geochemical variations of these lithologies can help refine LMO crystallisation models [7, 8]. Furthermore, by determining the crystallisation ages of the anorthosites, timing of LMO solidification can be constrained [5, 6].

However, anorthosites have had complex physical histories. Samples range from pristine igneous rocks to highly shocked cataclastic breccias [7]. To better understand the variation of lithophile geochemical signatures there is need to properly characterise the physical processes witnessed by these different samples.

Canonical interpretations of the anorthosite suite state that they have been shielded from the effects of lunar ‘surface’ solar wind and cosmogenic implantation processes for the majority of their history [9]. Indeed, pristine anorthosites typically only display short near-surface residence times (~20 Ma based on 38Ar and 81Kr systematics [10]). Therefore, anorthosites are ideally placed to also investigate the ‘indigenous’ (i.e., the noble-gas signature present since the formation of the Moon) noble gas signature of the Moon. The composition of which, has yet to be fully constrained in lunar samples [11,12].

Samples and Methods: We investigated 9 Apollo 16 anorthosites (65325, 62275, 67635, 60135, 69955, 60015, 60515, 62236, 67215) and Apollo 15 anorthosite 15415. Samples display a range of shock states from clear igneous textures to cataclastic high-shock (~20 GPa) textures. To liberate the Kr and Xe gas, we step heated ~10 mg sample chips using a diode laser (λ = 900 nm). In total 4 heating steps was undertaken. Two steps were conducted at low power (15, 25 W, < ~1000°C), a third over the melting point of the sample (35 W), and a fourth final high temperature (45 W) to ensure the liberation of all gas from the samples. The extracted gases cleaning used hot and cold charcoal getters for 15 mins before introduction on a Thermo Helix MC. Kr-Xe isotopes were measured using peak jumping mode. Ratios including small abundance isotopes display a long term typical reproducibly of ~20% RSD (e.g., blank corrected air-calibration of 126Xe/132Xe = 0.0037 (± 0.0008 (1σ), n= 27), for ratios of higher abundance isotopes typical long reproducibly is <2% RSD was achieved (e.g., blank corrected air-calibration of 126Xe/132Xe = 1.02 ± 0.02 (1σ), n= 27). Argon isotope data was analysed using irritated chips on an Thermo Argus VI for a parallel Ar-Ar dating study. All Ar-isotopes have been corrected for reactor produced interferences.

Result and Discussion: For the most part lunar noble gas systematics reflect a mixture of an implanted solar wind component, a trapped spallation product from cosmic rays, and spontaneous fission of radiogenic lithophile elements. Spontaneous fission of 238U, 244Pu, and 235U can act to increase 134,136Xe relative to 130,132Xe. Within this suite of samples, fission has had a negligible impact in modifying the noble-gas systematics, no samples display the expected enrichments in 134,136Xe. This is consistent with the generally low abundance of KREEP and elements such as U in anorthosites (< 1 ppb; [7]). However, 4 samples (62236, 62275, 67635, 15415) do display clear evidence some degree of cosmogenic spallation processes in their Kr and Xe isotope systematics (Fig. 1). In particular, plots of 124Xe/130Xe vs. 126Xe/130Xe indicate that spallation of Ba is dominant rather than spallation of the LREEs.

Cosmogenic processes are also reflected in the Ar-isotope systematics of these samples, which irrespective of temperature steps, display cosmogenic signatures (38Ar/36Ar = ~1.53). We calculated 38Ar exposure ages (using method by [13]) for these 4 samples which range from 71 Ma to 177 Ma. The other anorthosites have exposure ages <25 Ma, consistent with previously reported literature values. Plots of 40Ar/36Ar vs. 38Ar/36Ar illustrate that these samples are dominated by solar Ar isotope ratios, particularly at low temperature steps, reflecting the release of implanted solar wind that may be adhered to grain surfaces. However, in some cases the high temperature steps do record a cosmogenic dominated component. This component in the high temperature steps is not observed in the Kr-Xe isotope system, these samples cluster around solar/chondrite/air values in Kr-Xe isotope space.

Due to the isotopic similarity between terrestrial air and solar wind in Xe-isotope space it can be difficult to
differentiate between these components. Chemisorption of terrestrial atmospheric xenon rather than physical adsorption have been proposed as a mechanism to account for the air-like light Xe-isotope ratios \(^{124,132}\text{Xe}\) measured in lunar anorthosites to date [11]. The process of chemisorption is thought to be unique to the heavy noble gases, as the Ar-isotope systematics displays isotope ratios distinct from terrestrial air. However, it is likely that the Xe-isotope systematics reflects a mixture of both solar and adsorbed terrestrial air components.

Bekaert et al. [12] reported high precision Xe isotope data for 3 lunar anorthosites, one of which (65315) displays evidence of a depletion in the heavy Xe isotopes \(^{134,136}\text{Xe}\) relative to terrestrial air \(\left(\text{\^{136}Xe}/\text{\^{122}Xe}\right)_{\text{air}} = 0.98 \pm 0.01 \text{ 1}\sigma\). We also observe depletions in 7 of the anorthosites investigated here, in both high and low temperature steps. Depletions observed are much greater than observed by [12] \(\left(\text{\^{136}Xe}/\text{\^{122}Xe}\right)_{\text{air}} = 0.94 \pm 0.04 \text{ (1}\sigma\), to 0.67 \pm 0.12 \text{ (1}\sigma\)). Notably, these 7 samples encompassed both pristine igneous anorthosites and cataclastic anorthosites. The remaining samples are within error \(\text{(1}\sigma\) of terrestrial air, and are distinct from solar-Xe compositions, thus are likely to have been fully comprised by chemisorption of terrestrial air.

Solar Xe and chondritic xenon (Q-Xe) are not sufficiently depleted in both \(^{134}\text{Xe}\) and \(^{136}\text{Xe}\) to account for the observed depletions. Bekaert et al. [12] concluded that these signatures could represent a contribution from U-Xe mixing with a small cosmogenic and contaminated air contribution. The U-Xe component is thought to represent the precursor to modern terrestrial atmosphere [14, 15]. Whereas it has been debated if U-Xe represents a tangible component, recently studies have modeled that U-Xe represents a mixture of chondritic, solar, and cometary Xe [16]. This has led to suggestions that the observed \(^{134,136}\text{Xe}\) depletion in sample 65315 is the result of cometary addition to the Moon [12].

It is notable that both low and high temperature steps from this study display these depletions, indicating that these signatures are indeed a trapped component within minerals, rather than the result of surficial implantation. This is supported by the fact that depletions are observed in both samples that span the range of exposure ages determined for this suite, and display a wide range of shock textures. It is possible that icy bodies including cometary material was delivered to the Moon during the late veneer, prior to anorthosite crystallization. In this scenario, the observed \(^{134,136}\text{Xe}\) depletions would represent a true lunar indigenous component. Alternatively, implantation of the early Earth’s atmosphere into the lunar crust, has been proposed to have occurred (so called Earth winds’ [17]). Bekaert et al [12] ruled out this mechanism due to the short exposure ages of anorthosites reported in the literature. However, our samples display a much wider range of ages. Furthermore, exposure ages only represent relative surface ages, not absolute ages. If anorthosites were outcropping at the lunar surface following crystallization, or were brought to the lunar surface during basin forming impact events, it is possible that ancient Earth winds may have contributed a U-Xe like signature to the anorthosites at this time. This scenario is consistent with the recording of metamorphic or shock events during the basin forming period (~3.5 to ~4 Ga), as recorded by Ar-Ar dating studies [10], which indicates that lunar anorthosites have been profoundly affected by large impacts at this time. However, the samples with short (~20 Ma) exposure ages are consistent with the age of the South Ray crater near the Apollo 16 landing site. The matching of these ages has been used as evidence that it was the South Ray impact event that brought the Apollo 16 anorthosites to the lunar surface. In this scenario, it is hard to rule out the recent addition of icy body material to the lunar surface, via mechanisms such as micrometeorites. Overall, whereas the observation of \(^{134,136}\text{Xe}\) depletions in some lunar anorthosites reveals a tantalizing insight into indigenous lunar noble-gases, it is currently unclear to what extent processes, such as impact metamorphism or recent (<20 Ma) additions to the lunar regolith act to mask the indigenous lunar Xe signature.


Figure 1: Three isotope plots of Xe. Solar and cosmogenic end-members from [18]. Error bars represent 1\(\sigma\).