OXIDATIVE IMPACT PROCESSES REVEALED IN NORTHWEST AFRICA 11223. L. Qin[1,2,3], J.M.D. Day[1], K.T. Tait[4] [1]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093, USA (l3qin@ucsd.edu), [2]National Space Science Center, Chinese Academy of Sciences, Beijing, 100190, China, [3]University of Chinese Academy of Sciences, Beijing, 100049, China, [4]Royal Ontario Museum, Toronto, Canada

Introduction: Lunar impact melt rocks provide insights into processes acting on the Moon (e.g., [1-6]), as they formed during particular impact events and contain both target materials and material from the impactors themselves [4]. The compositions and sources of some impactors may also provide information on the dynamic impact history of the inner Solar System terrestrial planets [6]. During the last century, ~382 kg of lunar samples were brought back from the Moon during the Apollo and Luna missions, and chemical compositions of returned samples have been essential in constructing models and theories for the origin and evolution of the Moon. However, the six Apollo and three Luna sites were restricted to a small surface area of the Moon, optimistically, 5–8% [7], and have subsequently been shown to have a major contribution from a chemically anomalous region - the Procellarum KREEP Terrane (PKT) - located on the nearside of the Moon [8]. In contrast, lunar meteorites offer opportunities to randomly sample the lunar crust [9], including the areas distinct from the PKT. Thus, they are essential complements for understanding the Moon in lieu of new missions (e.g., Chang'e).

Northwest Africa (NWA) 11223 is a new lunar meteorite found in 2016 in southern Morocco and classified as a feldspathic lunar breccia [10]. Here, we present a comprehensive geochemical study of NWA 11223, including analysis of major, trace, and highly siderophile element (HSE: Re, Os, Ir, Pt, Pd, Ru) abundances and Os isotope ratios.

Methods: The bulk breccia was broken up into small pieces and then divided into two whole-rock samples (0.54 and 0.27 g) and six subsamples sorted crudely by lithology, weighing between 57 and 111 mg. Each sample was prepared by grinding into power in an alumina mortar and pestle. Two leaching experiments were also done on samples by treatment in hot 1M HCl to assess effects of terrestrial alteration. Major element compositions were measured by inductively coupled plasma-mass spectrometry (ICP-MS). Trace elements were determined via ICP-MS after the dissolution of powders in concentrated $HF+HNO_3$ along with terrestrial basaltic powder standards. For highly siderophile element analyses, samples were spiked for isotope dilution analysis prior to digestion in Carius tubes using aqua regia at 220°C for >36 h. Osmium was purified using solvent extraction and microdistillation. Iridium, Pu, Pt, Pd, and Re were isolated using anion exchange chemistry. Osmium isotope compositions and the remaining elements were measured by negative thermal ionization mass spectrometry (N-TIMS) and ICP-MS, respectively. All measurements were done at the *Scripps Isotope Geochemistry Laboratory*.

Results: Whole-rock compositions are consistent with the bulk mineralogy of the sample [10], with NWA 11223 being aluminum-rich (Al_2O_3 = 28.8-29.9%) with low concentrations of incompatible elements and positive Eu anomalies (Th = 0.17-0.18 ppm; *Fig. 1*), along with a FeO/MnO ratio of 68.8, indicating that the sample is a feldspathic lunar meteorite [9]. NWA 11223 is anomalous in that is has distinct negative Ce anomalies compared to most Apollo 17 KREEP-rich impact melt breccias and highland samples. The samples all have elevated abundances of highly siderophile elements (~0.007 × CI chondrite), but the osmium isotopic ratios of the samples analyzed so far have sub-chondritic measured $^{187}Os/^{188}Os$ (0.1228).

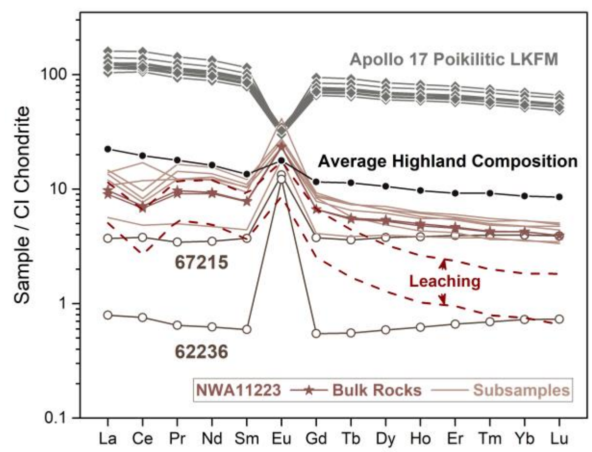

***Figure 1** CI-normalized REE patterns for NWA 11223 compared to Apollo 17 KREEP-rich impact melt breccias [1], the average lunar highland composition [11], and 'KREEP-free' rocks of the lunar crust (67215, 62236) [12]. Data source for CI chondrite from [13].*

Discussion:

Alteration. During the period between landing on Earth and discovery, meteorite finds may undergo low-temperature processes, leading to the enrichment and mobilization of some elements [14-15]. In order to adequately assess modification by terrestrial processes, acid-leaching experiments were conducted on NWA

11223. The leachates show enrichment in the light REE but do not remove the Ce anomaly. These results suggest that the Ce anomaly is related to formation of NWA 11223 on the Moon.

Source, KREEP components and oxidation. Together with a high Al_2O_3, the Fe/Mn ratio of the sample falls in the narrow range of lunar meteorites [9]. The major-element composition of NWA 11223 shows that it is feldspathic [10, 16], but may have a minor, KREEPy component, evident from the Sm concentration (1.2 ppm) [9]. This possibly implies a near-side origin for NWA 11223. The LREE pattern of NWA 11223 is similar in shape to those of Apollo 16 KREEP-poor rocks, but with higher absolute abundances and a notable Ce anomaly. The negative Ce anomaly indicates changes in oxidized state that converted Ce^{3+} to Ce^{4+}, and is most likely related to the lunar impact event(s) that formed NWA 11223.

Highly siderophile elements. Northwest Africa 11223 has elevated HSE abundances reaching the range of Apollo 17 impact melt breccias (*Fig. 2*). Bulk rock samples have relatively flat patterns, distinct from some Apollo 16 and 17 impact melt breccias. Notable features for NWA 11123 fragments is the low Ir and Os contents in one sub-sample. These variations are related to nugget heterogeneities in the guise of sulfide and metal in the sample.

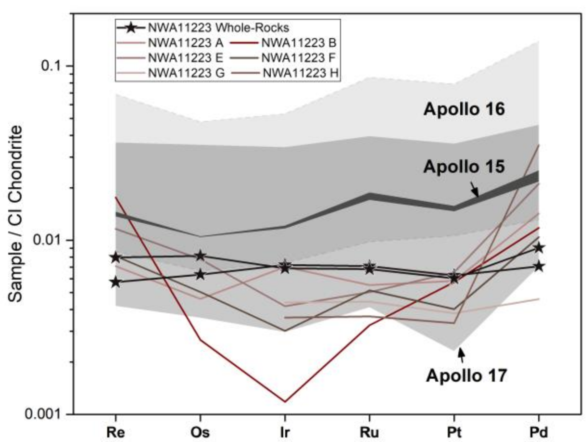

Figure 2 *CI-normalized highly siderophile element patterns for NWA 11223, Apollo 15 and Apollo 16 impact melt breccias [5], and Apollo 17 poikilitic impact melt breccias [1]. Data source for CI chondrite from [17].*

Osmium isotopes. The osmium isotopic compositions for whole-rocks are quite unradiogenic, whereas subsamples display variable $^{187}Os/^{188}Os$ ratios (*Fig. 3*). The Ru/Ir ratios for the bulk breccia are close-to-chondritic, while data for individual sub-fragments demonstrate the heterogeneity of the sample and variable fractionation of the HSE.

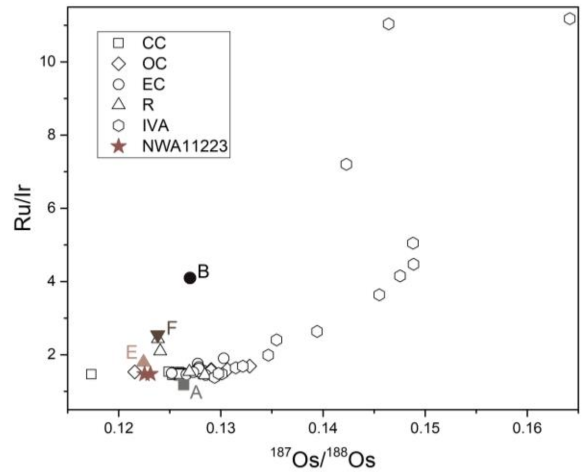

Figure 3 *Osmium isotopic ratios versus Ru/Ir ratios for NWA 11223, chondrites [17] and IVA irons [18].*

Summary: Pull-apart study of NWA 11223 reveals that bulk-rock samples have relatively low measured $^{187}Os/^{188}Os$ and chondritic relative HSE abundances, suggesting unusual carbonaceous or ordinary chondrite like impactors. Sub-fragments of the sample, however, indicate significant HSE variability and imply more than one impactor may be responsible for the composition of NWA 11223. The negative Ce anomalies in the meteorite also indicate that impactors striking the Moon can lead to significant changes in oxidation state either during the impact process or from delivery of reducing or oxidative materials from the impactors themselves. Meteorites, Apollo samples, and new missions to the Moon (i.e., Chang'e-5) all lead to a fuller picture of impactor populations and impact heritage of the Moon.

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