IMPACT PRODUCTION OF SILICON-BEARING IRON-NICKEL METAL: A WIDELY OCCURRING PROCESS ON THE MOON? N. G. LUNNING[1,2] and J. GROSS[1,2], [1]NASA Johnson Space Center ARES Mail Code XI2 2101 NASA Parkway Houston, TX, 77058-3696 (nicole.g.lunning@nasa.gov) [2]Rutgers, State University of New Jersey, Department of Earth and Planetary Sciences, 610 Taylor Road, Piscataway, NJ 08854-8066, USA

Introduction: Lunar samples, both meteorites and returned samples, are geologic archives of the evolution and history of the Moon. Metallic FeNi alloy particles occur in a wide range of lunar samples and provide insights into lunar geologic processes including lunar igneous evolution, space weathering, and meteoroid impact bombardment [1-3].

Prior to the last decade, only one study found Si-bearing metals in a lunar rock: meteorite Dhofar (Dho) 280 [4]. Recent work has dramatically increased the number of discoveries of Si-bearing metals in returned lunar samples and lunar meteorites [5-9]. However, the process (or processes) that formed these Si-bearing metals in lunar samples remains enigmatic.

Here, we describe additional discoveries of Si-bearing metal in the lunar feldspathic breccia Northwest Africa (NWA) 11303 and the petrographic context of these metals. We will use our newly discovered Si-bearing metal and those previously described to examine how Si-bearing metals form on the Moon.

Materials & Methods: We have investigated three polished thick sections of NWA 11301 that are part of the research collection of JG at Rutgers University. We have collected maps (BSE, CL, EDS, and WDS) of the entire sections and/or subsections with the JEOL JXA 8200 electron microprobe at Rutgers. We have also collected mineral point analyses with the Rutgers electron probe. Point analyses were collected at 15 KeV, 10-20 nA with spot sizes of 5 μm for plagioclase and glass and 1 μm for metal, sulfides, olivine, and pyroxene. REE concentrations for glass spherules associated with Si-bearing metal grains were determined using a Photon Machines laser ablation (LA) system and the Thermo Scientific iCAP Qc inductively coupled mass spectrometry (ICP-MS) system at Rutgers.

Results: We found several occurrences of Si-bearing metals in NWA 11303, but most FeNi metallic inclusions (5-200 μm) in this meteorite are not Si-bearing. The Si-bearing metals occur as two texturally zoned metallic spherules and as metallic grains in the outer rim of silicate glass spherules.

The two texturally zoned metallic spherules have exterior zones of polygonally fractured FeNi metal and unfractured smooth FeNi metal interiors. The larger texturally zoned metallic spherule (2D diameter of ~500 μm) has an average composition of 6.07 wt.% Ni, 91.9 wt. % Fe, and 1.35 wt. % Si. The smaller texturally zoned metallic spherule (2D diameter of ~30 μm) has an average composition of 9.45 wt.% Ni, 88.3 wt. % Fe, and 0.98 wt. % Si.

Fragments of two glass spherules are adjacent to each other on the edge of a thick section. Both spherules exhibit three textural zones in backscatter electron and CL images (Fig. 1); both glass spherules have an outer rim composed of dendritic microlites, a microlite-free region immediately interior to the rim, and another region even farther into interior with subtle rounded microlites. The metal grains (1-100 μm in their longest 2D dimensions) in the outer rims of the two silicate glass spherules have an average composition of 5.98 wt.% Ni, 87.7 wt. % Fe, and 5.82 wt. % Si. There are metallic grains in the interiors of the silicate glass spherules, but these metals are not Si-bearing.

The silicate portion does not differ in the major, minor, or REE concentrations between the two glass spherules and they do not exhibit compositional zoning within individual spherules. The glass spherules' silicate compositions closely resemble the bulk composition of feldspathic lunar meteorites [10].

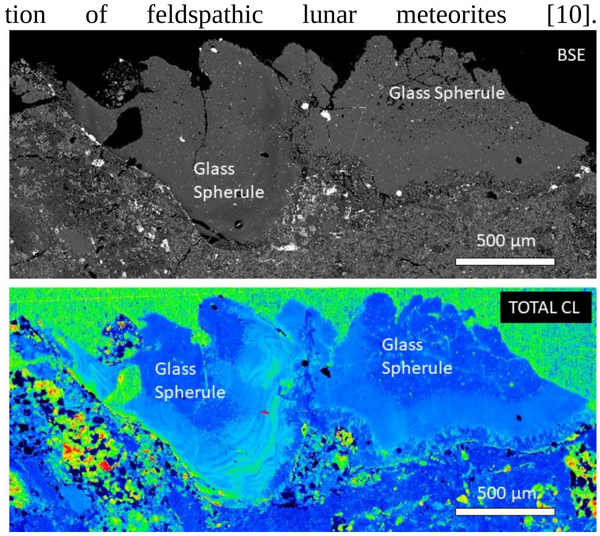

Figure 1: Glass spherule fragments in NWA 11303

Discussion: The texturally zoned Si-bearing metallic spherules in NWA 11303 are the first of this description reported within a lunar rock. It is an interesting occurrence that Si-bearing metals are also found in rims of the only silicate glass spherules recognized in this lunar meteorite – we are considering the possibility that metallic spherules and the glass spherules formed in the same event. The glass spherules probably formed by ejection of impact melt of a lunar regolith that closely resembles the meteorite in which they are found.

There are three general mechanisms that could form Si-bearing metal in lunar samples: (1) Space weathering [4], (2) Incorporation of meteoritic impactors that would bring Si-bearing metals to the Moon [e.g., 11], (3) Impact-related modification of impactors and lunar target materials to form Si-bearing metals [7-8]. We will discuss these three possibilities below.

Space weathering was proposed as the formation mechanism for the first identified Si-bearing FeNi metal phases in a lunar meteorite by [4]. In the subsequent 15 years, a diverse range of analytical and experimental studies of lunar space weathering have been undertaken, which have not found other evidence for Si-bearing FeNi metal or native Si formation during lunar space weathering [e.g., 3]. Nanophase-Fe remains the only widely recognized metallic lunar space weathering product (i.e., not Si-bearing Fe or native Si). This is consistent with results of vacuum evaporation experiments that demonstrate Fe consistently evaporates from silicate liquids at lower temperatures and more rapidly than Si [12-13].

Several meteorite types that could be impactors onto the Moon contain Si-bearing FeNi metals, specifically, aubrites, enstatite chondrites, and a handful of ungrouped irons [14]. Both aubrites and enstatite chondrites are primarily composed of end-member Mg-pyroxene (enstatite); if the Si-bearing metals came from these meteorite types there should be complementary enstatite in NWA 11303. However, we analyzed the most Mg-rich silicate grains based on whole section element maps and all of these grains were too Fe-rich. The Si-bearing ungrouped irons are incredibly rare among iron meteorites (5 out of 1263) [15], which prompts us to view this possibility with skepticism.

Impact modification of lunar target materials and/or impactors encapsulates multiple processes that are not mutually exclusive: condensation of impact-generated vapor plumes, shock modification, melting at pressure and temperature conditions that may be unique to impact crater environments. Nazarov et al. [7] proposed that the Si-bearing FeNi metals and native Si discovered in Dho 280 required a very large impact – possibly the South Pole Aiken forming impact – to form the vapor plume from which these materials could condense. If this is the case, all of the Si-bearing FeNi metals found come from same impact or a very small number of impact events on the Moon, which is difficult to reconcile with the occurrences of Si-bearing FeNi metals in Apollo 16 regolith samples [8] as well as the feldspathic lunar meteorites [4,7, this study], which likely originate from very different geographic locations on the Moon [e.g., 16]. The impact energy to form a vapor plume that would condense Fe-Ni-Si and/or native Si is not well understood. The chemical interaction between impact melt and vapor plumes is an area of active research with many unanswered questions. However, recent work suggests that for the Mg-Si-O liquid-gas system in impact environments, Si-species disproportionately go into the vapor phase relative to Mg-species [17].

All of the recognized Si-bearing metals in lunar samples do not have to form via vapor plumes to be the result of impact modification of lunar target and impactor materials. Experimental studies have demonstrated that shock modification can form Si-bearing metals, as well as the polygonal texture observed in the outer zone of the NWA 11303 metallic spherules [e.g., 18]. In addition, Si-bearing FeNi metals have been identified at the terrestrial impact sites associated with the Wabar and Gebel Kamil iron meteorites, which are not themselves Si-bearing iron meteorites [19-20]. The Si-bearing FeNi metal is found within silicate impact melt units at these terrestrial impact sites. Impact experiments that used iron meteorites as impactors onto silicate rock targets have also recognized Si-bearing FeNi in their experimental products [21]. Thus, for iron meteorite impacts onto the moon, Si-bearing metals may form as condensates from vapor plumes or within melt zones.

Conclusions: Impacts onto the Moon may have formed Si-bearing FeNi metals through multiple mechanisms during a given impact event. Recent discoveries of Si-bearing FeNi metals in a wide variety of lunar rocks indicate that either (1) a limited number of large impacts are responsible for the formation of all these Si-bearing metals which were subsequently redistributed across the lunar surface or (2) Si-bearing FeNi metals can form via more moderately sized impact events and thus have been formed by numerous events throughout lunar history.

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