NWA 10989 – A NEW LUNAR METEORITE WITH EQUAL PROPORTIONS OF FELDSPATHIC AND VLT MATERIAL H. O. Ashcroft[1], M. Anand[1,2], R. L. Korotev[3], R. C. Greenwood[1], I. A. Franchi[1] and S. Strekopytov[4] [1]School of Physical Sciences, The Open University, Milton Keynes, UK. [2]Department of Earth Sciences, Natural History Museum, London, UK [3]Department of Earth & Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis MO 63130. [4]Imaging and Analysis Centre, The Natural History Museum, London, UK. (email: mahesh.anand@open.ac.uk).

Introduction: Northwest Africa 10989 (NWA 10989) is a new lunar meteorite found near to the Morocco/Algeria border and acquired in 2015. NWA 10989 is a single stone, weighing 14.41 g with a dark brown fusion crust and is classified as a mixed lunar fragmental breccia [1]. Terrestrial weathering is limited and is mainly apparent as some carbonate veins. Here we present a preliminary report on the mineralogy and geochemistry of NWA 10989, discuss the potential sources of individual components, and compare it with other, similar meteorites.

Methods: A petrographic study was performed on a polished thin section of the sample using an optical microscope and a SEM. Mineral chemistry was determined using an EPMA. Bulk rock analysis was determined using INAA [2], and oxygen isotope analysis was performed using infrared laser-assisted fluorination [3].

Confirmation of Lunar Origin: Pyroxene and olivine grains diplay ranges in Fe/Mn of 63±11 and 105±11 respectively, which are consistent with known lunar trend lines [4], [5]. Oxygen isotopes are also consistent with a lunar origin with $\delta^{17}O$ 3.42 ‰, $\delta^{18}O$ 6.51 ‰, $\Delta^{17}O$ 0.03 ‰.

Petrology and Mineralogy: NWA 10989 (Fig. 1) is a polymict breccia containing mm-sized minerals, lithic and impact-melt clasts in a dark brown glassy matrix, in which vesicles can be seen in addition to smaller mineral fragments and lithic clasts. Mineral fragments show a diverse range of composition (Fig. 2) and are predominantly feldspar (An_{80-99}), pyroxene ($Wo_{3-42}En_{5-75}Fs_{15-64}$) and olivine ($Fo_{5-76}$). Accessory minerals include spinel, ilmenite, apatite, merrilite, silica, troilite, kamacite and schreibersite. Generally, minerals do not exhibit compositional zoning, and many pyroxenes exhibit exsolution lamellae which are ~1 μm thick. Evidence for shock is seen in some feldspar grains through recrystallization and partial maskylenitisation, and offset lamellae are observed in pyroxene. NWA 10989 can be subdivided into three main areas based on texture and composition (Fig. 1a).

Area 1 is dominated by a partially devitrified impact glass which contains few mineral fragments. Average composition for this area (from multiple EPMA spot analysis) is 49 wt. % SiO_2, 1.15 % TiO_2, 11.8 % Al_2O_3, 6.58 % MgO, 12.0 % CaO, 18.0 % FeO, 0.38 % Na_2O and 0.05 % K_2O.

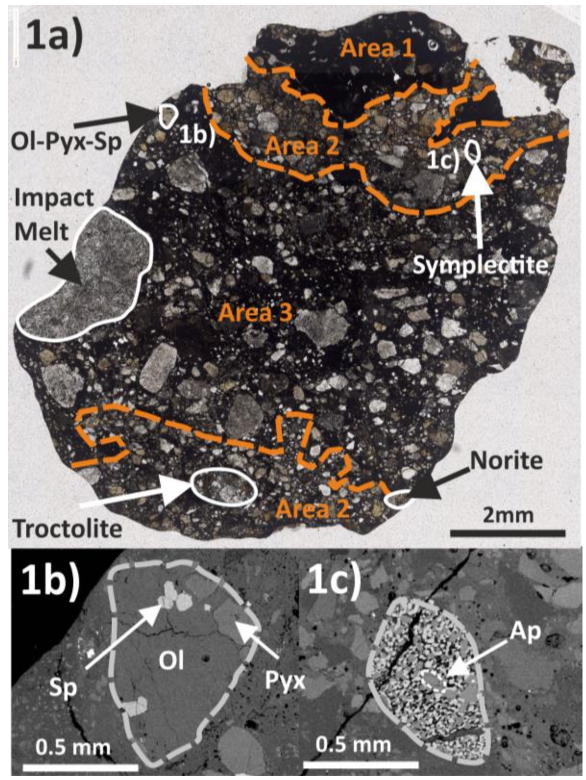

Figure 1. a) a full Mosaic image of the NWA 10989 thin section taken for the Virtual Microscope highlighting the different petrographic domains, and a variety of clasts. b) a pyroxene-olivine-spinel clast, c) symplectite of Fayalite-Quartz-Hedenbergite with an apatite crystal in the centre.

Area 2 is a crystal dominated breccia with a seriate texture, with mineral fragments up to 100s of μm in size with rare lithic and impact-melt fragments. Pyroxenes in this region (defined in Fig. 2a and b as the 'clastic area') show a very-low-Ti (VLT) trend on a Ti# vs. Fe# plot, and this region contains a fayalite-silica-hedengbergite symplectite which also has a single, euhedral apatite (Fig. 1c).

Area 3 contains mm-sized lithic and impact-melt clasts, and is comprised of roughly equal proprotions of matrix and clasts. Lithic clasts include anorthosite/norite, troctolite, granulite and plutonic-looking clasts comprising olivine (Fo_{60-68}), pyroxene ($Wo_{12-39}En_{47-63}Fs_{14-28}$) and spinel (Al-chromite) (Fig. 1b). The impact melt clasts can be subdivided into groups based on their texture and composition. Some are large (mm size) with a microbasaltic texture, dominated by feldspar with minor pyroxene, olivine and spinel (labelled as Impact Melt Clast 1 (IMC 1) on Fig. 2). Others contain intergrown feldspar and pyroxene in equal proportions (IMC 2 on Fig. 2). Other textures vary from cryptocrystalline, to glassy, to breccia-in-breccia textures. There is a variation in matrix and impact-melt composition from basaltic to feldspathic. The boundaries between Areas 2 and 3 are gradational.

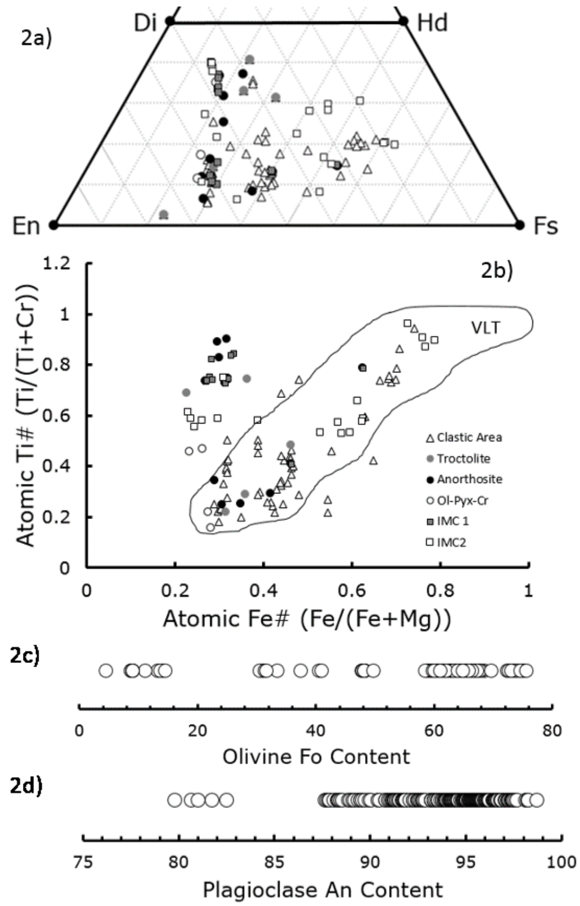

Figure 2. a) NWA 10989 pyroxene compositions b) Ti# vs. Fe# for pyroxenes in the meteorite c) olivine forsterite contents d) plagioclase anorthite contents. The VLT field outlined in 2b) includes the data for Apollo 17 VLT pyroxenes [6], Luna 24 pyroxenes [7] and pyroxenes from several lunar meteorites [8],[9].

Bulk Composition: Bulk composition of NWA 10989 (12.6 wt. % FeO, 1.04 ppm Th, 25.5 ppm Sc, 2154 ppm Cr and 4.3 ppb Ir) is consistent with the petrographic classification as a mixed breccia. There are roughly equal proportions of basaltic and feldspathic material suggested by the intermediate FeO and Sc contents, and the shape of the chondrite-normalised REE pattern, which has a small negative Eu anomaly.

Discussion: Compositionally NWA 10989 appears to share some features with a few other lunar meteorites, in particular the NWA 7834 clan. Similarities to other subgroups include the NWA 7611 clan and also the well characterized paired group which includes NWA 4884, YAM 981031, YAM 793274 and QUE 94281 (plotted on Fig. 3 for comparison). The Ti contents of the VLT trend pyroxenes were used to calculate parental bulk magma TiO_2 of ~ 1 wt. % (method in [8]). At least two distinct compositional sources have contributed material to NWA 10989 – a highlands source for the lithic clasts and plagioclase with high An content, and a VLT-like basaltic melt. From bulk, mineral and clast compositions a probable source region for NWA 10989 is an area on the highlands-mare boundary such as on the lunar nearside, potentially close to the Luna 24 or Apollo 17 landing sites. Future work will investigate the range of impact-melt compositions, and provenance of the minerals and clasts seen in more detail. Age dating of individual components will also be performed.

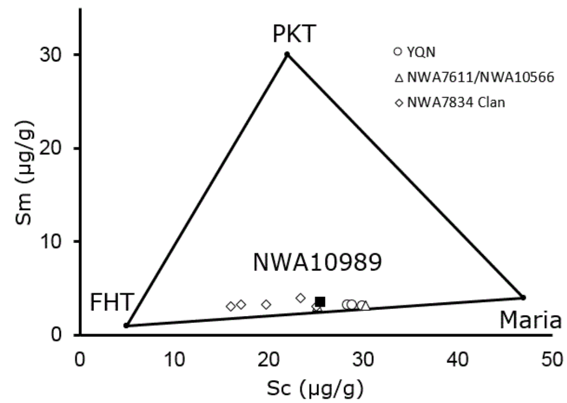

Figure 3. Bulk Sm vs Sc contents of NWA 10989. Other lunar meteorites have been plotted for comparison including YAM 981031 [10], QUE 94281 [11] and NWA 4884 [12] (YQN group), the NWA 7611 and NWA 7834 clans [1]).

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