COMPOSITION OF FINE-GRAINED BULK MATRIX AND PROTOBRECCIA CLAST MATRIX IN NORTHWEST AFRICA 7034: IMPLICATIONS FOR THE COMPOSITION OF THE MARTIAN CRUST.

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Introduction: The martian meteorite Northwest Africa (NWA) 7034 and pairings is different from other martian meteorites in that it is a breccia. NWA 7034 has a basaltic bulk composition, and initial studies of NWA 7034 determined that its major element bulk composition coincides with the composition of the average martian crust [1-3], including the bulk compositions of several rocks and soils measured on the martian surface by the Mars Exploration Rovers (MER) [4-5]. Consequently, this meteorite represents the strongest link between a martian meteorite and the martian surface determined by remote sensing.

Given the similarities between NWA 7034 and estimates of the composition of the bulk martian crust, we set out to examine, in detail, the composition of various portions of the NWA 7034 matrix. Specifically we focus on determining the bulk composition of the micron to sub-micron bulk matrix [defined in 6] as well as the micron to sub-micron matrix material of protobreccia clasts [defined in 6] that occur within NWA 7034 because this material represents the finest fraction of material within the meteorite and hence may provide important constraints on the bulk composition of the martian crust. Once the major and minor element compositions were determined by EPMA, we analyzed the same regions by LA-ICP MS to determine trace element abundances, which we then compare to previous estimates for the trace element composition of the martian crust.

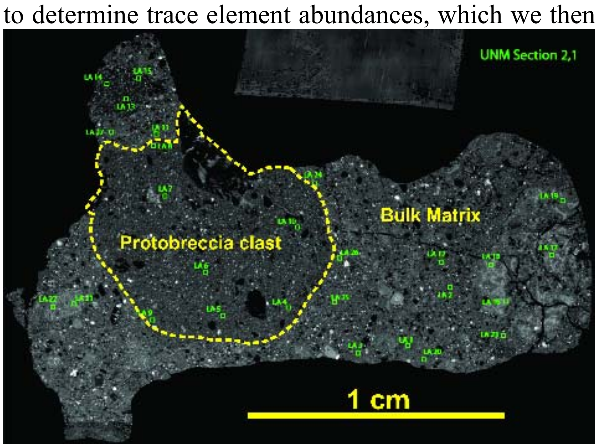

Figure 1. BSE image of NWA 7034 section with protobreccia clast and bulk matrix identified in yellow. EPMA/LA-ICP MS anlaysis regions are identified in green.

Bulk Matrix Domain: The bulk matrix domain of NWA 7034 consists of the interconnected, fine-grained (0.1-5 µm), crystalline groundmass that holds the meteorite together. The fine-grained portion of the groundmass consists of 0.1-1 µm sized pyroxene, plagioclase, phosphate, and FeTi-oxide phases, including a nanophase Fe-hydroxide [7]. This material is holocrystalline and shows evidence of mild thermal annealing based on interlocking submicron grain boundaries that meet at 120° angles [7]. Figure 1 contains images of the bulk matrix, which was previously referred to as fine grained basaltic porphyry by [1] and as interclast crystalline matrix (ICM) by [8].

Proto-breccia Clasts: Clasts with non-igneous textures are grouped under the term proto-breccia clasts [defined in 6]. These clasts typically consist of fine grained matrix surrounding coarser mineral fragments or other clast types. The matrix of this clast type is composed of fine grained, crystalline mineral phases, similar to the bulk matrix. This combination of coarse material surrounded by fine material is typical of breccias, and they likely represent fragments of a breccia that existed prior to the assembly and lithification of NWA 7034. Their matrix and grain boundaries are distinct from the interconnected bulk matrix domain of NWA 7034, allowing them to be distinguished as a separate clast type. The matrix within these clasts has a different texture and modal phase abundance than the bulk matrix domain. Proto-breccia clasts range in size from 0.9 x 0.2 mm to 11 x 12 mm (Figure 1). Mineral fragments tend to be the same mineralogy as observed in the bulk rock matrix and include feldspar, pyroxene, FeTi-oxides, and apatite.

Methods: EPMA was conducted using a JEOL JXA 8200 electron microprobe equipped with 5 wavelength dispersive spectrometers in the IOM at UNM. Analyses were conducted using a 40 µm beam diameter, 15 keV accelerating voltage, and 15 nA beam current. Grids of points (4x4) equivalent in size to LA-ICP MS spots were set up on the bulk and proto-breccia clast matrix. Individual analyses were normalized to 100% totals then averaged to determine the composition of both matrix types. The major element composition of individual grid areas was determined by averaging the 16 normalized analyses within the grid. LA-ICP-MS analyses were conducted with a UP213 laser ablation system coupled to an Element2 HR-ICP-MS using the instrument parameters and procedures outlined in Simonetti and Neal [9].

Discussion: The composition of the fine-grained matrix within NWA 7034 bears a striking resemblance to the major element composition estimated for the martian crust, with several exceptions. The NWA 7034 matrix is depleted in Fe, Ti, and Cr and enriched in Al, Na, and P. The differences in Al and Fe are the most substantial, but the Fe could be explained if the NWA 7034 matrix material is more representative of the ancient southern highlands crust, as suggested by [8] based on the ancient 4.4 Ga ages recorded in NWA 7034 zircons. The Fe content of the southern highlands (14-18 wt.% FeO) is markedly lower than the northern lowlands (18-24 wt.% FeO) [10], and the Fe abundance in the NWA 7034 matrix falls within the range reported for the southern highlands.

The elevated abundance of siderophile elements such as Ni in NWA 7034 compared to martian shergottites has been used as evidence for approximately 5% CI chondrite contamination in NWA 7034 [8]; however, the Ni abundance of NWA 7034 matrix is very similar to estimates of Ni in the bulk martian crust, which had already been corrected for 2% CI addition [3]. Consequently, we do not see evidence for substantial chondritic contamination in the fine-grained fraction of NWA 7034. In fact, 4.2% chondritic contaminant would leave no Ni in the bulk crust, which is unrealistic.

The NWA 7034 matrix material is enriched in incompatible trace elements compared to estimates of the bulk martian crust by a factor of 1.2-1.5 [3]. Furthermore, La/Yb of the bulk martian crust is estimated to be ~3 [3], and the La/Yb of the NWA 7034 matrix materials range from approximately 4.1 to 4.4, indicating a higher degree of LREE enrichment in the NWA 7034 matrix materials. This elevated La/Yb ratio and enrichment in incompatible lithophile trace elements is consistent with NWA 7034 representing a more geochemically enriched crustal terrain than is represented by the bulk martian crust, which would be expected if NWA 7034 represents the bulk crust from the southern highlands.

Additional work is being conducted to better constrain the abundances of additional elements so that better constraints can be placed on the amount of chondritic contamination in NWA 7034 and the degree of geochemical enrichment in the portion of the martian crust represented by NWA 7034 matrix.

Table 1a. Major and minor element compositions (wt.%) for NWA 7034 and estimates of the average Martian crust [3].

Oxide	Bulk Matrix	Protobreccia Clast	Average martian soil[3]	Average Martian Crust[3]
SiO_2	48.05	49.94	48.35	49.3
TiO_2	0.75	0.65	0.96	0.98
Al_2O_3	12.14	14.83	10.34	10.5
Cr_2O_3	0.17	0.15	0.38	0.38
FeO_T	15.99	12.55	17.81	18.2
MnO	0.34	0.26	0.35	0.36
MgO	11.24	9.13	8.89	9.06
CaO	6.00	7.04	6.78	6.92
Na_2O	3.22	3.79	2.91	2.97
K_2O	0.51	0.42	0.47	0.45
P_2O_5	1.42	1.16	0.88	0.9
Cl	0.16	0.126	0.72	-
S	0.09	0.025	2.63	-
-O	0.08	0.04	1.48	-
Total	100.00	100.00	100.00	100.00

Table 1b. Average trace element compositions (ppm) for NWA 7034 and estimates of the average Martian crust.

Element	Bulk Matrix	Protobreccia Clast	Average martian soil[3]	Average Martian Crust[3]
Ni	390	290	490	337
Zn	92	78	286	320
Rb	9	5	-	12.5
Y	21	33	-	18
Ba	92	94	-	55
La	8.4	13	-	5.5
Ce	21	35	-	13.9
Pr	3.0	4.8	-	1.9
Nd	13	22	-	9.4
Sm	3.6	5.9	-	2.7
Eu	1.1	1.26	-	0.95
Tb	0.63	1.0	-	0.55
Gd	3.9	6	-	3.1
Dy	4.1	7	-	3.4
Ho	0.80	1.3	-	0.7
Er	2.2	3.5	-	1.9
Tm	0.31	0.5	-	0.25
Yb	2.1	3.0	-	1.7
Lu	0.28	0.39	-	0.26
Th	1.1	2.0	-	0.70
U	0.29	0.36	-	0.18

References: **[1]** Agee et al., (2013) *Science*, 339, 780-785. **[2]** McSween et al., (2009) *Science*, 324, 736-739. **[3]** Taylor and McLennan (2008) *Planetary Crusts*, 378pp. **[4]** Gellert et al., (2006) *JGR-Planets*, 111. **[5]** McSween et al., (2006) *JGR-Planets, 111.* **[6]** Santos et al., (2015) *GCA*, In press. **[7]** Muttik et al., (2014) *GRL*, in press. **[8]** Humayun et al., (2013) Nature, 503, 513-516. **[9]** Simonetti and Neal, (2010) *EPSL*, 295, 251-261. **[10]** Boynton et al., (2007) *JGR-Planets, 112.*