

Geochemistry and petrography of martian meteorite Northwest Africa 11115: A rare earth element-enriched olivine-phyric shergottite closely linked to Northwest Africa 1068

Mohit Melwani Daswani¹, Nicolas Greber², Jinping Hu³, Richard Greenwood⁴, and Philipp Heck⁵

¹Jet Propulsion Laboratory, California Institute of Technology

²Institute of Geological Sciences, University of Bern

³Division of Geological and Planetary Sciences, California Institute of Technology

⁴The Open University

⁵Field Museum of Natural History

November 22, 2022

Abstract

The shergottite family of meteorites shows a remarkable petrographic and geochemical variety, revealing information about mantle processes and basalt formation on Mars. Northwest Africa (NWA) 11115, found in Morocco in 2016, is one of the newest meteorites in this family. We report bulk-rock major and trace element abundances of NWA 11115, bulk oxygen isotope systematics, and the petrography and mineralogy of a thick section, and compare the geochemistry of this recent find to other martian rocks. NWA 11115 is an olivine-phyric shergottite with an enriched rare earth element pattern, and shares similarities with NWA 1068, another enriched olivine-phyric shergottite. The large (< 2.5 mm) olivine phenocrysts are likely to be cumulates, similar to NWA 1068. However, the abundant maskelynite (~ 30 vol. %) in NWA 11115 places the bulk chemistry somewhat closer to the basaltic shergottites. We suggest that NWA 11115 is genetically linked to NWA 1068, perhaps crystallizing slightly above in the same cumulate pile. NWA 11115 contains one of the lowest K/Th ratios among the martian meteorites ($K/Th = 2987 \pm 810$), and far lower than the surface of Mars ($K/Th = 5300$). Finally, while NWA 11115 contains abundant (~ 0.4 vol. %) fracture-filling calcite (presumably from hot desert alteration during its terrestrial residence), diagnostic bulk element mass ratios were not indicative of the presence of terrestrial alteration (Th/U [?] 4.09, Sr/Nd [?] 12.26, K/La [?] 526.94, Ce/Ce^* [?] 1.01).

Geochemistry and petrography of martian meteorite Northwest Africa 11115: A rare earth element-enriched olivine-phyric shergottite closely linked to Northwest Africa 1068

M. Melwani Daswani^{a*,†}, N. D. Greber^{b, c}, Jinping Hu^d, R. C. Greenwood^e, and P. R. Heck^{a, f}

^a Department of the Geophysical Sciences and Chicago Center for Cosmochemistry, University of Chicago, Chicago, IL 60637, USA.

^b Natural History Museum of Geneva, Route de Malagnou 1, 1208, Geneva, Switzerland

^c Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland

^d Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E. California Blvd. M/C170-25, Pasadena, CA, 91125, USA.

^e Planetary and Space Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK.

^f Robert A. Pritzker Center for Meteoritics and Polar Studies, Negaunee Integrative Research Center, The Field Museum of Natural History, Chicago, IL 60605, USA.

* Corresponding author (mohit.melwani.daswani@jpl.nasa.gov)

[†] Now at the Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109, USA.

Abstract

The shergottite family of meteorites shows a remarkable petrographic and geochemical variety, revealing information about mantle processes and basalt formation on Mars. Northwest Africa (NWA) 11115, found in Morocco in 2016, is one of the newest meteorites in this family. We report bulk-rock major and trace element abundances of NWA 11115, bulk oxygen isotope systematics, and the petrography and mineralogy of a thick section, and compare the geochemistry of this recent find to other martian rocks. NWA 11115 is an olivine-phyric shergottite with an enriched rare earth element pattern, and shares similarities with NWA 1068, another enriched olivine-phyric shergottite. The large (< 2.5 mm) olivine phenocrysts are likely to be cumulates, similar to NWA 1068. However, the abundant maskelynite (~30 vol. %) in NWA 11115 places the bulk chemistry somewhat closer to the basaltic shergottites. We suggest that NWA 11115 is genetically linked to NWA 1068, perhaps crystallizing slightly above in the same cumulate pile. NWA 11115 contains one of the lowest K/Th ratios among the martian meteorites ($K/Th = 2987 \pm 810$), and far lower than the surface of Mars ($K/Th = 5300$). Finally, while NWA 11115 contains abundant (~0.4 vol. %) fracture-filling calcite (presumably from hot desert alteration during its terrestrial residence), diagnostic bulk element mass ratios were not indicative of the presence of terrestrial alteration ($Th/U \approx 4.09$, $Sr/Nd \approx 12.26$, $K/La \approx 526.94$, $Ce/Ce^* \approx 1.01$).

37 1. INTRODUCTION

38 Northwest Africa (NWA) 11115 is a martian shergottite meteorite found at an undisclosed location in
39 Morocco in 2016. A 34.2 g aliquot of the main mass (246.76 g) was donated to the Field Museum of Natural
40 History (FMNH) in Chicago by T. Boudreaux, and its official name was approved in February 2017 (The
41 Meteoritical Society 2017). Here, we describe the geochemistry, mineralogy and petrography of NWA 11115
42 in relation to other martian meteorites and the surface of Mars, we use oxygen isotope systematics to confirm
43 its provenance, and we show that it belongs to the uncommon group of rare earth element (REE) enriched
44 olivine-phyric shergottites.

45
46 In the following work, we provide a general introduction to the shergottite meteorites to provide context
47 for the study of NWA 11115. We then explain the analytical methods used to study chemical composition,
48 oxygen isotopes, mineralogy and petrography of NWA 11115 in §2, and then report the detailed results of the
49 analyses in §3. In §4, we discuss and interpret the results, focusing on the provenance of NWA 11115 and its
50 relationship to other shergottites, and the evidence for terrestrial weathering. Finally, we provide our
51 conclusions and suggestions for further study of NWA 11115 in §5.

53 1.1. Shergottites: a primer

54 Martian meteorites probe the chemistry of the interior of Mars, and complement the analyses and
55 discoveries carried out by landed and orbiting spacecraft. The petrologic and geochemical properties of martian
56 materials are characteristic of specific geologic processes that occurred on Mars and can, for example, inform
57 about the degree of magmatic differentiation, volcanism, aqueous alteration and the effects of impact.
58 Therefore, every martian meteorite recovered is scientifically significant in that it can help unravel a portion
59 of Mars' geologic history. Until samples are returned from Mars, the only martian rocks physically available
60 for study in terrestrial laboratories are meteorites. Of the 152 currently named martian meteorites, the
61 shergottites are the most numerous group, comprising 132 rocks as of May 2021, not counting paired rocks,
62 i.e. fragments belonging to the same meteor (Irving 2021). The shergottites' geochemical, mineralogic and
63 petrographic characteristics have informed about the composition of the martian mantle, crust and atmosphere,
64 and about igneous processes and the formation of basalts on Mars.

65 Petrographically and mineralogically, the shergottites are broadly divided into the olivine-phyric, poikilitic
66 (formerly lherzolitic), and pyroxene-phyric/basaltic groups (e.g., Goodrich 2002; Papike et al. 2009). The
67 olivine-phyric shergottites (e.g. NWA 2990, Tissint and Yamato 980459) are related by their olivine-porphyrific
68 textures within finer-grained groundmass, with low augite contents, and with chromite in addition to Fe-Ti
69 oxides. The olivine-phyric shergottites represent rocks that crystallized from melt (e.g. Y-980459) or that
70 contain olivine crystal cumulates (Filiberto and Dasgupta 2011; e.g., Usui et al. 2008). The poikilitic
71 shergottites (e.g. Allan Hills 77005 and NWA 2646) are coarse-grained and the most olivine-rich (~30 – 60
72 vol. % olivine) of the shergottites. They additionally contain pyroxene, chromite and maskelynite, and are
73 likely cumulates (e.g., Goodrich 2002; Papike et al. 2009). On the other hand, the pyroxene-phyric/basaltic

meteorites (e.g. Zagami, Shergotty, NWA 7032, NWA 7635 and NWA 8159) are a diverse group containing almost no olivine and chromite, but instead are almost entirely formed of augite, pigeonite and maskelynite, and vary widely in their grain size, probably as a result of different cooling rates within lavas (e.g. Goodrich, 2002; Papike et al., 2009). Finally, polymict breccia NWA 7034 and its pairs contain numerous matrix-supported clasts of varying petrologic types and compositions that match the shergottite lithologies (e.g. Agee et al., 2013; Humayun et al., 2013; Wittmann et al., 2015; Santos et al., 2015).

Separate from their petrologic grouping, shergottites are also divided geochemically into the light rare-earth element (LREE) enriched, intermediate, and depleted groups (e.g. McSween, 1994; Filiberto, 2017), relative to the abundance of their heavy REE (HREE), and CI chondrite REE concentrations. Enriched shergottites (e.g. Shergotty and NWA 4468) have moderately flat REE abundance profiles with no significant enrichments or depletions in any specific REE ($\text{La/Yb} > 0.7$). However, their REE abundances are all $\sim 10 \times$ enriched relative to CI chondrites, most likely as a result of subsolidus equilibration, melt fractionation and assimilation from crustal sources (e.g. Treiman, 1996; Borg and Draper, 2003; Papike et al., 2009). Depleted shergottites (e.g. NWA 7032 and Tissint) have significantly different LREE concentrations relative to their HREE abundances ($\text{La/Yb} < 0.3$), and the LREE tend to be depleted compared to CI chondrites ($\text{LREE} < 1 \times \text{CI chondrite LREE}$). Finally, the intermediate shergottites are somewhat more enriched in HREE relative to LREE ($0.3 < \text{La/Yb} < 0.7$), and their overall REE abundances are somewhat elevated compared to CI chondrites ($1 - 10 \times \text{CI chondrite REE}$) (e.g. Papike et al., 2009; Taylor, 2013).

2. ANALYTICAL METHODS

2.1. X-ray computed tomography

Before cutting, the complete specimen of NWA 11115 was scanned using X-ray computer tomography (CT) with a GE v|tome|x s 240 scanner at the University of Chicago's PaleoCT lab. X-ray CT enabled us to quantify the porosity of the meteorite and the interconnectivity of the pores. We used a voltage of 190 kV and a current of 150 μA at a voxel size of 30.3 μm ; a 0.5 mm Sn filter was used. The total scan time was 6 hours 43 minutes. The scan was performed in several segments that were stitched together in the reconstruction. We used the *Fiji* distribution of the *ImageJ* software (Schindelin et al. 2012) to analyze the tomographic dataset. The tomographic reconstruction is available in the electronic appendix.

2.2. Mineralogy and petrography using electron microscopy

A chip of NWA 1115 was cut using water-free high-purity (Optima™) isopropanol with a low-speed Buehler IsoMet wafering saw outfitted with a thin diamond blade. The chip was embedded in a 1-inch diameter epoxy round (Buehler EpoxiCure® 2; pre-2016 formulation), polished with diamond film and water-free Optima™ isopropanol, and coated with carbon for characterization by electron microscopy. The sample was analyzed at the FMNH with a Zeiss EVO 60 Scanning Electron Microscope (SEM) equipped with an Oxford Instruments X-Max 50 silicon drift detector, and at the University of Chicago with a TESCAN LYRA3 FIB-

SEM equipped with two Oxford Instruments X-Max-80 silicon drift detectors. Quantitative analyses of the mineral compositions, backscattered electron (BSE) and elemental mapping were carried out with Oxford Instruments energy dispersive spectroscopy (EDS) systems attached to both SEMs, with a 15 kV acceleration voltage and a beam current of ~2-4 nA. We used a set of mineral reference standards to calibrate the EDS, and calibrated and monitored stability of the e-beam current by using bracketed analyses of a Cu standard in between 10 – 20 sample spots. We report only compositions that give total weights of 100 ± 2 wt. %. Oxford Instruments' *AZtec* software was used to produce the raw BSE and element map images; *Fiji* and the *GNU Image Manipulation Program* (GIMP) were used to produce image composites, for mineral phase mapping and for modal mineralogy.

119

2.2.1. Bulk composition using LA-ICP-MS

121

Around 0.462 g of NWA 11115 were milled with an agate mortar to measure major and trace elements by LA-ICP-MS on “Pressed Powder Pellets” following the protocol of Peters and Pettke (2017) at the University of Bern. The USGS glass standard GSD-1G was used for instrument calibration. To check the accuracy of the analyses the basaltic reference glass KL2-G was measured three times before and after the analyses of the unknowns. Due to limited sample availability, we were not able to produce a powder with a grain size of below 5 μm , and certain elements like Cr and P_2O_5 might thus be subjected to nugget effects (due to chromite and apatite, respectively). Therefore, to obtain a representative average of the major and trace element concentration of NWA 11115 we performed 27 consecutive analyses. Except for Cr, the mean and median values of the 27 individual analyses agree to around ± 5 % with each other, indicating that our data is representative of the bulk rock. In addition, Se concentrations measured in the KL2-G standard differed from the values reported in literature, so we consider the Se concentrations measured in NWA 11115 to be uncertain and report them only in the Supplementary Spreadsheet File S1. We note that we reported preliminary bulk geochemical analyses of this meteorite (Melwani Daswani et al. 2017), but that those results were likely contaminated or affected by the sample preparation procedure. The results we report below are the authoritative version. We include the sidelined analyses in the Supplementary Information for comparison and completion.

137

2.2.2. Oxygen isotope systematics using laser fluorination

The oxygen isotopic composition of NWA 11115 was determined by infrared laser-assisted fluorination at the Open University on two aliquots of homogenized powder each weighing ~2 mg (Greenwood et al. 2017; Miller et al. 1999) at the Open University. These were loaded into a Ni sample block along with obsidian internal standards. The sample block was then positioned into a two-part chamber, made vacuum tight using a compression seal fitted with a copper gasket and clamped by a quick-release KFX clamp (Greenwood et al. 2017; Miller et al. 1999). Following loading, the cell was heated under vacuum for a minimum of 24 hours to a temperature in excess of 70 °C so as to remove any adsorbed atmospheric moisture. Prior to fluorination, the

system blank was systematically reduced by flushing the chamber with aliquots of BrF₅, with the final blank being less than 60 nmol O₂. Sample heating in the presence of BrF₅ was carried out using an integrated 50 W infrared CO₂ laser (10.6 μm) and video system mounted on an X-Y-Z gantry supplied by Photon Machines Inc. (Greenwood et al., 2017). After fluorination, the released O₂ was purified by passing it through two cryogenic (liquid nitrogen) traps and over a bed of heated KBr. The isotopic composition of the purified oxygen was analyzed using a Thermo Fisher MAT 253 dual inlet mass spectrometer (mass resolving power 200). Interference at m/z = 33 by NF⁺ was monitored by performing scans for NF₂⁺ on the sample gas before analyzing each sample; this was below interference levels during the analyses reported here. Our current system precision based on repeat analyses (N = 39) of our obsidian internal standard is: ± 0.052 ‰ for δ¹⁷O; ± 0.094 ‰ for δ¹⁸O; ± 0.017 ‰ for Δ¹⁷O (2σ) (Starkey et al. 2016). Oxygen isotopic analyses are reported in standard δ notation, where δ¹⁸O has been calculated as: δ¹⁸O = [(¹⁸O/¹⁶O_{sample}/¹⁸O/¹⁶O_{ref}) - 1] × 1000 (‰) and, similarly, for δ¹⁷O using the ¹⁷O/¹⁶O ratio. In order to compare our results with other published laser fluorination analyses of martian samples we have calculated Δ¹⁷O, which represents the deviation from the terrestrial fractionation line, as Δ¹⁷O = δ¹⁷O - 0.52 × δ¹⁸O.

3. RESULTS

3.1. Petrography and mineralogy

The 1-inch round polished thick section of NWA 11115 consists of about 4 % pore space. We report the porosity-removed modal mineralogy: olivine forms approximately 14 %, pyroxene (mainly pigeonite) forms ~ 50 %, and plagioclase (as maskelynite) around ~ 30 %. The remainder consists of ~ 0.3 % sulfides, ~ 0.3 % orthopyroxene, ~ 2 % Fe-Ti-Cr-oxides, ~ 2 % phosphates, and trace K-feldspar and silica (Figure 1). Abundant (~ 0.4 %) secondary Mg-rich calcite (almost certainly produced by terrestrial fluids) infills pores, especially within the numerous cracks in and around olivine grains. Most mineral phases are medium grained and subhedral, except for sulfides and Fe-oxides, which are fine-grained. Olivine crystals up to 2.5 mm across are visible, along with elongated grains of pyroxene of about the same length. Maskelynite infills the interstices between grains, and mineral grains follow no preferential orientation. Also visible within the section are numerous shock melt pockets of mixed pyroxene and feldspathic glass. Overall, the large grain size of the olivine and pyroxene in the sample is consistent with martian gabbros (e.g. NWA 6963; Filiberto et al., 2014) rather than typical olivine-phyric shergottites, whose olivine grains are significantly larger than the remaining mineral phases (mostly pyroxene and plagioclase), and which form a fine-grained groundmass or matrix (e.g. NWA 6234/2990; Gross et al., 2013). However, the modal mineralogy of NWA 11115 lies between pyroxene-phyric/basaltic and olivine-phyric shergottites, i.e. it contains significant amounts of plagioclase, but also contains olivine. The tomographic reconstruction shows the same lithology throughout the complete sample of NWA 11115 (electronic appendix), thus, we infer that the polished section is a representative sample of the entire rock. Average compositions of the main mineral phases are shown in Table 1.

182

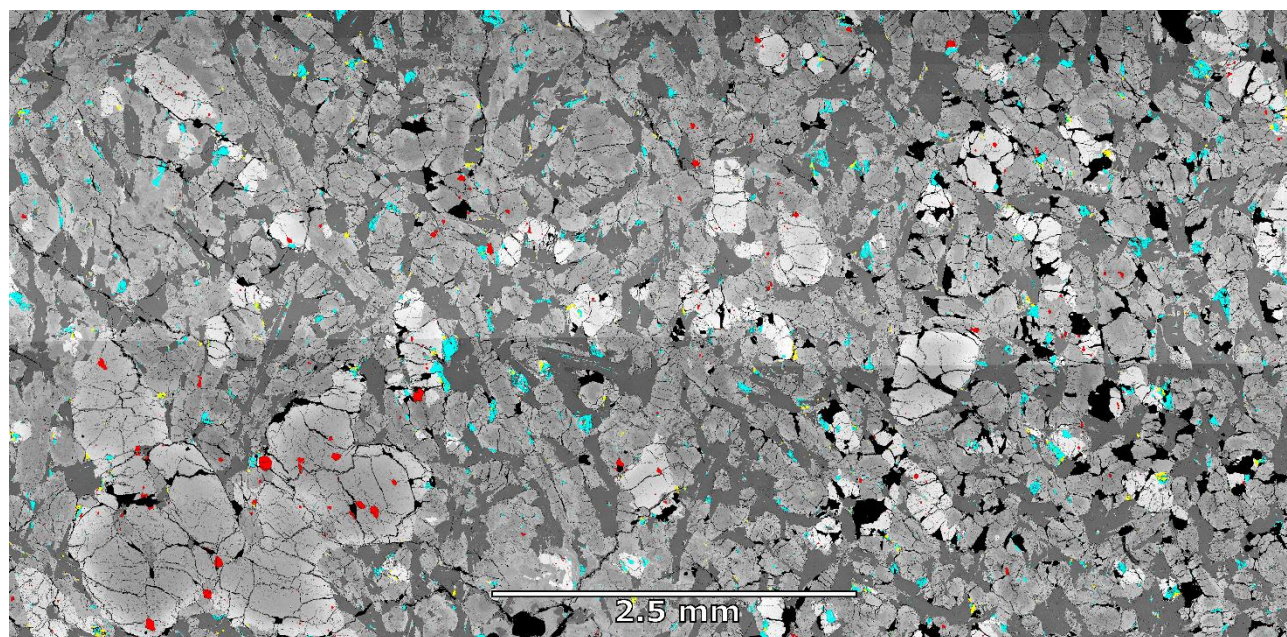


Figure 1. BSE image mosaic of a representative section of NWA 11115. Refractory phases are colored in the image in order to distinguish them: chromite grains are red, ilmenite grains are blue, and sulfides are yellow. Black areas are secondary pores and fractures.

183

Table 1. Average major oxide concentrations of the major phases in the thick section.

	^a Olivine		^b Pigeonite		Enstatite		Augite		Maskelynite	
	N = 57		N = 24		N = 8		N = 2		N = 74	
	Wt. %	±1σ	Wt. %	±1σ	Wt. %	±1σ	Wt. %	±1σ	Wt. %	±1σ
SiO ₂	34.68	1.91	51.60	1.07	53.95	0.42	21.22	0.54	55.81	1.22
TiO ₂	nd ^c	-	0.22	0.17	bdl ^d	-	0.37	0.04	bdl	0.03
Al ₂ O ₃	nd	-	1.54	0.33	0.45	0.20	1.54	0.33	27.10	0.81
Cr ₂ O ₃	nd	-	0.40	0.19	0.41	0.06	0.63	0.02	nd	-
FeO _T ^e	41.00	9.35	20.94	3.28	16.49	0.27	17.14	2.32	0.76	0.17
MnO	0.78	0.18	0.69	0.14	0.58	0.06	0.60	0.01	nd	-
MgO	22.71	7.87	18.60	3.02	25.03	0.31	16.09	1.01	0.02	0.05
CaO	0.26	0.11	5.26	1.35	2.21	0.12	11.32	2.40	9.90	0.93
NiO	nd	-	nd	-	nd	-	nd	-	nd	-
Na ₂ O	nd	-	bdl	-	bdl	-	bdl	-	5.40	0.42
K ₂ O	nd	-	nd	-	nd	-	nd	-	0.34	0.09
P	0.03	0.09	bdl	-	bdl	-	bdl	-	nd	-
S	0.05	0.27	nd	-	nd	-	nd	-	nd	-
Total	99.50	0.81	98.71	0.59	99.11	0.87	98.89	1.12	99.34	0.93
Mg#	48.88	14.29	61.03	7.46	73.02	0.41	62.66	1.70		
Fe/Mn	53.01	6.43	30.44	2.79	28.84	2.80	28.53	3.19		

Fo	48.88	14.29							
Wo			11.11	2.94	4.43	0.24	24.08	5.51	
Fs			34.55	6.21	25.79	0.34	28.39	3.35	
An									49.30 4.42
Ab									48.66 3.95
Or									2.05 0.57

^aThe compositions of zoned olivine are averaged for modeling bulk mineral abundance. See text for chemical zoning of olivine. ^bSee Fig. 3 for compositions of zoned pigeonite. ^cNot determined. ^dBelow detection limit. ^eIncludes Fe₂O₃.

3.1.1. Olivine

Olivine crystals in NWA 11115 are 250 μ m to 2.5 mm in size and are mostly subhedral. All olivine grains show some degree of chemical zonation from core to rim, although the larger crystals more strongly so ($\sim$ Fo₇₀ to Fo₄₅); smaller olivine grains are much more ferroan ($\sim$ Fo₂₁ to Fo₃₅). Some larger olivine crystals appear to form clumps or glomerophyres consisting of annealed crystals, and each sub-crystal contains its own distinct chemical zonation from core to rims (Figure 2). We address the origin of the olivine crystals in §4.1.

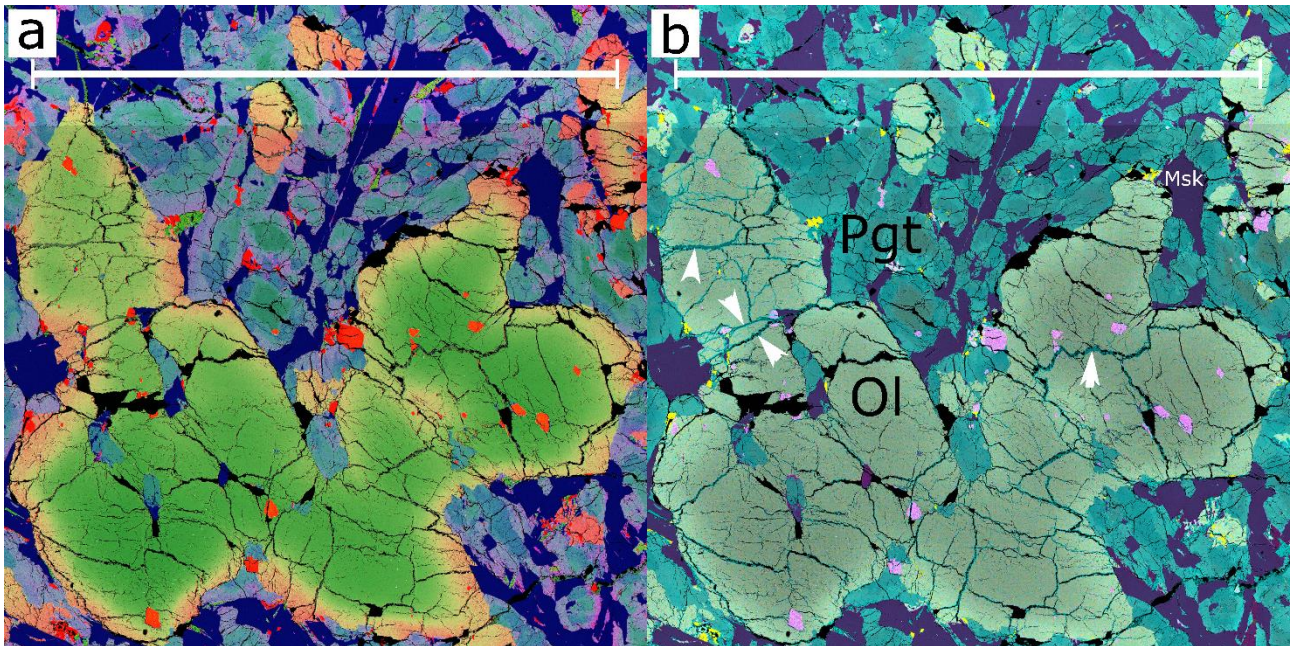
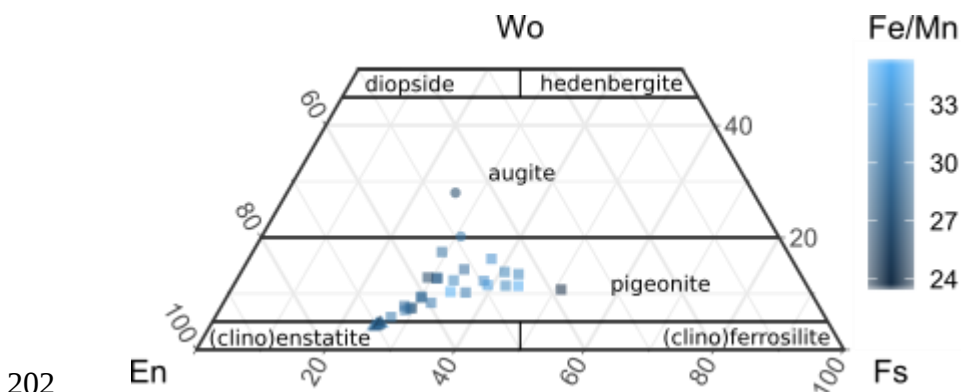


Figure 2. False color composites of an olivine glomerophyre surrounded by maskelynite and pigeonite, and with numerous spinel grains. A) Red = iron, green = magnesium, blue = silicon. B) Cyan = calcium, yellow = sulfur, magenta = aluminum. Abundant calcite (arrows) infills fractures in the olivine phenocrysts. The scale bar is 2.5 mm across.

3.1.2. Pyroxene

Most pyroxene crystals in the meteorite are subhedral to anhedral pigeonite, with grain sizes comparable to the olivine grains, reaching up to $\sim$ 2 mm in length. The pigeonite crystals are compositionally zoned from

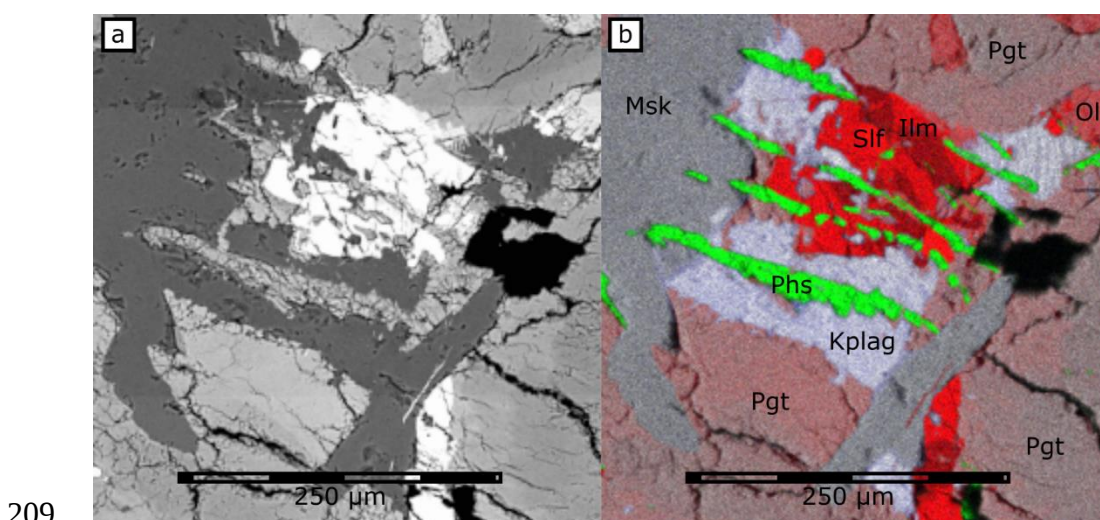
199 core to rim (Figure 1 & Figure 2). Enstatite and augite are also present as accessory grains in the sample.
 200 Analyzed pyroxene compositions are shown in Table 1 and Figure 3.
 201



202
 203 *Figure 3. Compositional variability of the pyroxenes in NWA 11115. Darker points indicate lower Fe/Mn mass ratios and lighter points represent higher Fe/Mn mass ratios.*

203 3.1.3.Maskelynite

204 Plagioclase feldspar in NWA 11115 is found in the form of maskelynite. Most of the plagioclase is K-poor (<
 205 0.5 wt%) and does not exhibit substantial compositional variation (Table 1), however, some accessory K-
 206 enriched plagioclase does occur ($K \approx 5\text{--}10$ wt. %; Figure 4). These K-enriched alkali feldspar zones are most
 207 often found adjacent to Ca-rich phosphate minerals and Cr-Fe-Ti-oxides (Figure 4).
 208



209
 210 *Figure 4. Complex mineral intergrowths of K-rich plagioclase, phosphate, and Cr-Fe-Ti spinel. A) BSE image. B) False color composite. Red = iron, green = phosphorus, blue = potassium, background = silicon. Mineral abbreviations are: Msk = maskelynite, Kplag = K-rich plagioclase, Phs = phosphate, Pgt = pigeonite, Ol = olivine, Ilm = ilmenite, Slf = sulfide.*

3.1.1. Iron oxides and sulfides

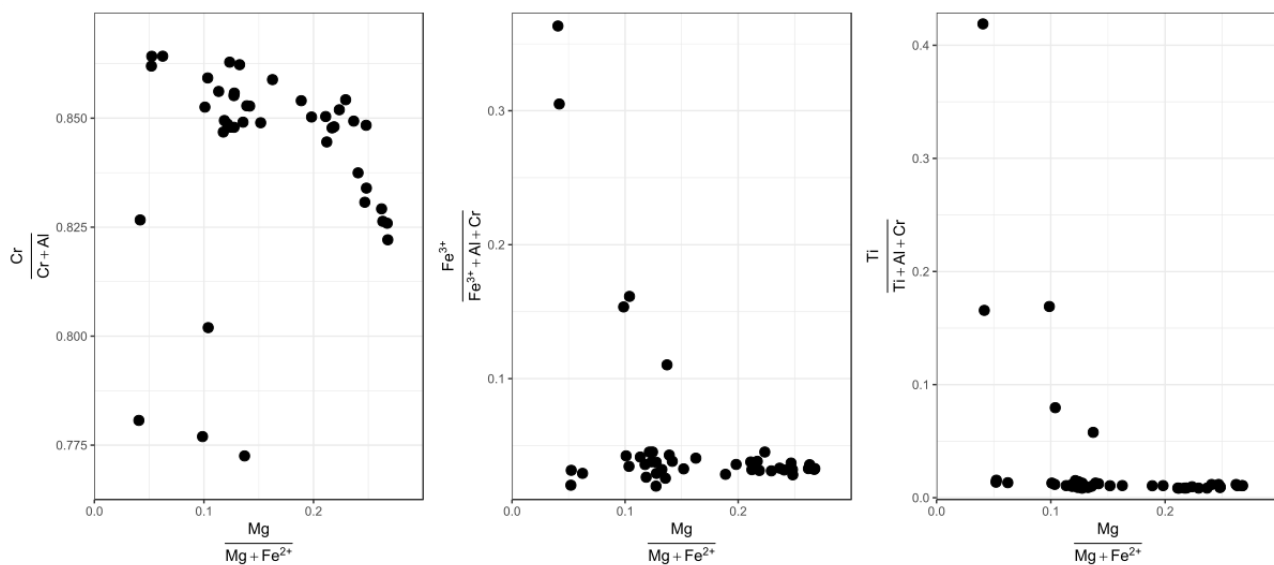
Spinel minerals are abundant throughout NWA 11115, poikilitically growing in olivine and pyroxene grains, but also occurring separately adjacent to olivine and pyroxene grains. The spinel minerals are intergrown magnesian chromite – hercynite – ulvöspinel solid solutions (Table 2 and Figure 5), that occasionally also intergrow with sulfides (Figure 4). Individually measured compositions are therefore variable, as for example in their TiO₂ concentration. Spinel grains with higher concentration of magnesium also tend to have higher concentration of aluminum and lower concentration of chromium (Figure 5). Spinels with higher concentration of Ti tend to occur in contact with phosphates and K-rich feldspar (Figure 4).

Table 2. Composition of spinel group minerals in NWA 11115 (*n* = 42).

	Wt. %			
	Mean	25 % quartile	Median	75 % quartile
SiO ₂	0.36	0.30	0.35	0.38
TiO ₂	1.68	0.69	0.77	0.89
Al ₂ O ₃	6.63	6.34	6.64	6.83
Cr ₂ O ₃	53.51	55.65	56.26	56.69
V ₂ O ₃	0.52	0.40	0.44	0.59
Fe ₂ O ₃ ^a	3.52	2.29	2.52	2.97
FeO	29.38	26.69	29.38	30.03
MnO	0.60	0.52	0.61	0.67
MgO	3.12	2.27	2.68	4.31
CaO	0.01	0	0	0
ZnO	0.14	0.01	0.11	0.24
Total	99.46	99.18	99.52	99.82
apfu ^c				
Si	0.01	0.01	0.01	0.01
Ti	0.05	0.02	0.02	0.02
Al	0.28	0.27	0.28	0.28
Cr	1.50	1.54	1.57	1.59
V	0.01	0.01	0.01	0.02
Fe ³⁺	0.09	0.06	0.07	0.08
Fe ²⁺	0.87	0.79	0.88	0.89
Mn	0.02	0.02	0.02	0.02
Mg	0.16	0.12	0.14	0.23
Ca	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.01

Total	3.00	3.00	3.00	3.00
Atomic ratios				
Mg/(Mg+Fe ²⁺)	0.16	0.12	0.14	0.22
Cr/(Cr+Al)	0.84	0.83	0.85	0.85
Fe ³⁺ /(Fe ³⁺ +Al+Cr)	0.06	0.03	0.04	0.04
Ti/(Ti+Al+Cr)	0.03	0.01	0.01	0.01
Endmember molar composition ^d				
MgAl ₂ O ₄ ^e	0.02	0.02	0.02	0.03
FeAl ₂ O ₄ ^f	0.12	0.11	0.12	0.12
MgFe ³⁺ ₂ O ₄ ^g	0.01	0.00	0.01	0.01
Fe ²⁺ Fe ³⁺ ₂ O ₄ ^h	0.04	0.02	0.03	0.03
MgCr ₂ O ₄ ⁱ	0.12	0.09	0.11	0.18
FeCr ₂ O ₄ ^j	0.63	0.59	0.64	0.69
MnCr ₂ O ₄ ^k	0.01	0.01	0.01	0.02
FeV ₂ O ₄ ^l	0.01	0.00	0.01	0.01
Fe ₂ TiO ₄ ^m	0.02	0.01	0.01	0.01

220 ^aCalculated on the basis of stoichiometry, using the method of Droop (1987) implemented in Ferracutti et
 221 al. (2015). ^bBelow detection limit. ^cAtoms per formula unit. ^dCalculated with the End-Members Generator
 222 (Ferracutti et al. 2015), for spinel group minerals with the formula $X^{2+}Y^{3+}_2O_4$, for a total charge of 8, normalized
 223 here to 1 mol. ^eSpinel. ^fHercynite. ^gMagnesioferrite. ^hMagnetite. ⁱMagnesiochromite. ^jChromite.
 224 ^kManganochromite. ^lCoulsonite. ^mUlvöspinel.
 225



226

Figure 5. Compositional diversity in spinel group minerals analyzed in NWA 11115 ($n = 42$). All spinel
 minerals analyzed are Cr-rich.

227

228 3.1.2. *Phosphates*

229 Phosphates in NWA 11115 consist primarily of subhedral, elongated (up to ~ 0.6 mm) and fractured
 230 merrillite crystals, although minor amounts of chlorine-bearing apatite are also found in the sample (Table 3).
 231 Phosphate crystals are typically found in contact with K-rich feldspar and Cr-Fe-Ti spinels (Figure 4).
 232

Table 3. Phosphates in NWA 11115.

Elements	Apatite	Merrillite	
	N = 1	N = 25	
	Wt. %	Wt. %	$\pm 1\sigma$
O	39.63	41.67	0.44
Na	bdl ^a	1.24	0.17
Mg	bdl	1.37	0.12
Al	bdl	0.01	0.03
Si	0.24	0.07	0.13
P	18.62	20.42	0.31
S	bdl	0.02	0.11
Cl	1.34	bdl	nd
Ca	37.85	33.04	0.36
Mn	bdl	0.02	0.05
Fe	0.70	2.31	0.25
Total	98.37	100.10	0.99
Calculated OH (= 100 – total – Cl)	0.29	-	-
	<i>apfu</i> ^b	<i>apfu</i>	$\pm 1\sigma$
O ^c	12	28	-
Na	0	0.58	0.08
Mg	0	0.61	0.05
Al	0	0	0.01
Si	0.04	0.03	0.05
P	2.91	7.09	0.06
S	0	0.01	0.04
Cl	0.18	0	-
Ca	4.58	8.86	0.11
Mn	0	0	0.01
Fe	0.06	0.44	0.05
Total +1 cations	0	0.58	0.08

Σ +2 and +3 cations 4.64 9.92 0.09

^aBelow detection limit. ^bAtoms per formula unit. ^cCations are normalized to the ideal number of oxygen atoms per formula unit, i.e. 12 oxygen atoms in apatite (Ca₅(PO₄)₃(F,Cl,OH)) and 28 oxygen atoms in merrillite (Ca₉NaMg(PO₄)₇).

3.1.3. Melt pockets

The numerous melt pockets in NWA 11115 appear to be composed of a mixture of primary minerals. Representative chemical analyses of three melt pockets are shown in Table 4. We used least-squares regression to calculate the mixing ratio of each of the mineral components that form three representative melt pockets. As mineral endmembers, we used the mean of the olivine, pyroxene (including enstatite, pigeonite and augite), maskelynite, merrillite and spinel compositions of NWA 11115 that we report here (Table 1 to Table 3). Additionally, we added stoichiometric pyrite as an endmember since we have not yet carried out detailed analyses of the sulfide compositions in the meteorite. The results of the regression calculation are shown in Table 4.

Table 4. Compositional analyses of three melt pockets in NWA 11115, and results of the linear least-squares regression calculation to determine the proportion of mineral phase endmembers that form the melt pockets.

	Melt pocket 1		Melt pocket 2		Melt pocket 3	
	N = 2		N = 3		N = 1	
	Wt. %	$\pm 1\sigma$	Wt. %	$\pm 1\sigma$	Wt. %	
SiO ₂	50.17	0.32	48.91	1.26	50.40	
TiO ₂	0.55	0.10	0.60	0.02	0.38	
Al ₂ O ₃	0.73	0.07	0.60	0.02	0.90	
Cr ₂ O ₃	bdl ^a	-	0.32	0.09	0.36	
FeO _T ^b	27.46	0.54	21.75	1.11	23.80	
MnO	0.78	0.01	0.54	0.05	0.74	
MgO	14.16	0.98	12.48	0.35	16.08	
CaO	5.72	0.47	9.27	0.76	5.58	
Na ₂ O	bdl	-	0.71	0.70	bdl	
K ₂ O	bdl	-	bdl	-	bdl	
P	bdl	-	1.22	0.02	bdl	
S	bdl	-	1.05	0.19	bdl	
Total	99.55	0.27	101.03	1.05	98.24	
Mg#	47.86	2.23	50.58	1.96	54.64	
Linear regression	Mixing ratio	Standard Error	Mixing ratio	Standard Error	Mixing ratio	Standard Error

Olivine	0.26	0.17	0.01	0.16	0.14	0.10
Pyroxene	0.66	0.20	0.82	0.19	0.79	0.12
Plagioclase	0.10	0.09	0.09	0.09	0.07	0.05
Spinel	0.00	0.05	0.01	0.05	0.01	0.03
Merrillite	0.01	0.03	0.06	0.04	0.01	0.02
Pyrite	0.03	0.05	0.06	0.04	0.02	0.03
Adjusted R ²		0.98		0.98		0.99

^aBelow detection limit. ^bTotal Fe, including FeO and Fe₂O₃.

3.1. Bulk-rock geochemistry

Bulk sample chemistry of *Sample-UniBern* obtained by LA-ICP-MS (Table 5) revealed that NWA 11115 is generally similar to other martian shergottites. Supplementary Table 1 contains the disregarded LA-ICP-MS analysis carried out of *Sample-FMNH*, and an EMPA major element analysis on the same sample.

Bivariate Harker diagrams (Figure 6) allow for effective comparison of major element abundances between NWA 11115 and other martian meteorites. The concentration of major oxides in NWA 11115 is consistent with basaltic shergottites, apart from the MgO content, which lies between the average concentration in basaltic shergottites and in olivine-phyric shergottites (Figure 6). The average magnesium number ($100 \times \text{Mg}/(\text{Fe} + \text{Mg})$) of NWA 11115 is $\text{Mg\#} = 57.35$. NWA 11115 shows an enriched REE pattern, similar to other enriched shergottites, between NWA 856 and Los Angeles (Figure 7).

Table 5. Whole rock chemistry of NWA 11115 *Sample-UniBern*, obtained by LA-ICP-MS from 27 repeat analyses. Oxides are reported in wt. %, and individual elements in $\mu\text{g/g}$. See Supplementary Information and Supplementary Spreadsheet File S1 for sidelined FMNH analyses and calibration measurements.

	Mean	$\pm 2\sigma$
SiO ₂	47.90	1.09
TiO ₂	0.74	0.28
Al ₂ O ₃	6.53	0.97
FeO _T	20.97	1.43
MnO	0.51	0.03
MgO	12.27	0.74
CaO	8.67	0.48
Na ₂ O	1.30	0.18
K ₂ O	0.18	0.04
P ₂ O ₅	0.73	0.21
Li	4.34	0.50

Be	0.37	0.15
B	3.66	0.98
Sc	44.69	4.23
V	232.17	41.30
Cr	2348.05	1560.64
Co	47.00	4.04
Ni	138.03	20.90
Cu	15.44	4.62
Zn	91.22	13.44
Ga	14.79	2.52
Ge	0.80	0.12
As	0.19	0.04
Rb	6.86	2.91
Sr	56.13	6.77
Y	17.55	5.46
Zr	57.27	22.97
Nb	3.84	1.80
Mo	0.13	0.04
Ag	0.01	0.01
Cd	0.04	0.02
In	0.03	0.01
Sn	0.30	0.08
Sb	0.01	0.01
Cs	0.46	0.22
Ba	62.47	7.77
La	2.92	1.00
Ce	6.82	2.45
Pr	0.94	0.35
Nd	4.68	1.70
Sm	1.76	0.63
Eu	0.67	0.20
Gd	2.72	0.97
Tb	0.48	0.15
Dy	3.32	1.04
Ho	0.68	0.21
Er	2.01	0.58
Tm	0.26	0.07
Yb	1.76	0.42

Lu	0.25	0.06
Hf	1.69	0.60
Ta	0.18	0.09
W	0.50	0.15
Tl	0.03	0.01
²⁰⁸ Pb	0.70	0.33
Bi	0.004	0.003
Th	0.51	0.14
U	0.13	0.02
Mg#	57.35	1.68

260 ^aAt or below the detection limit. Values represent maximum concentration measured.

261

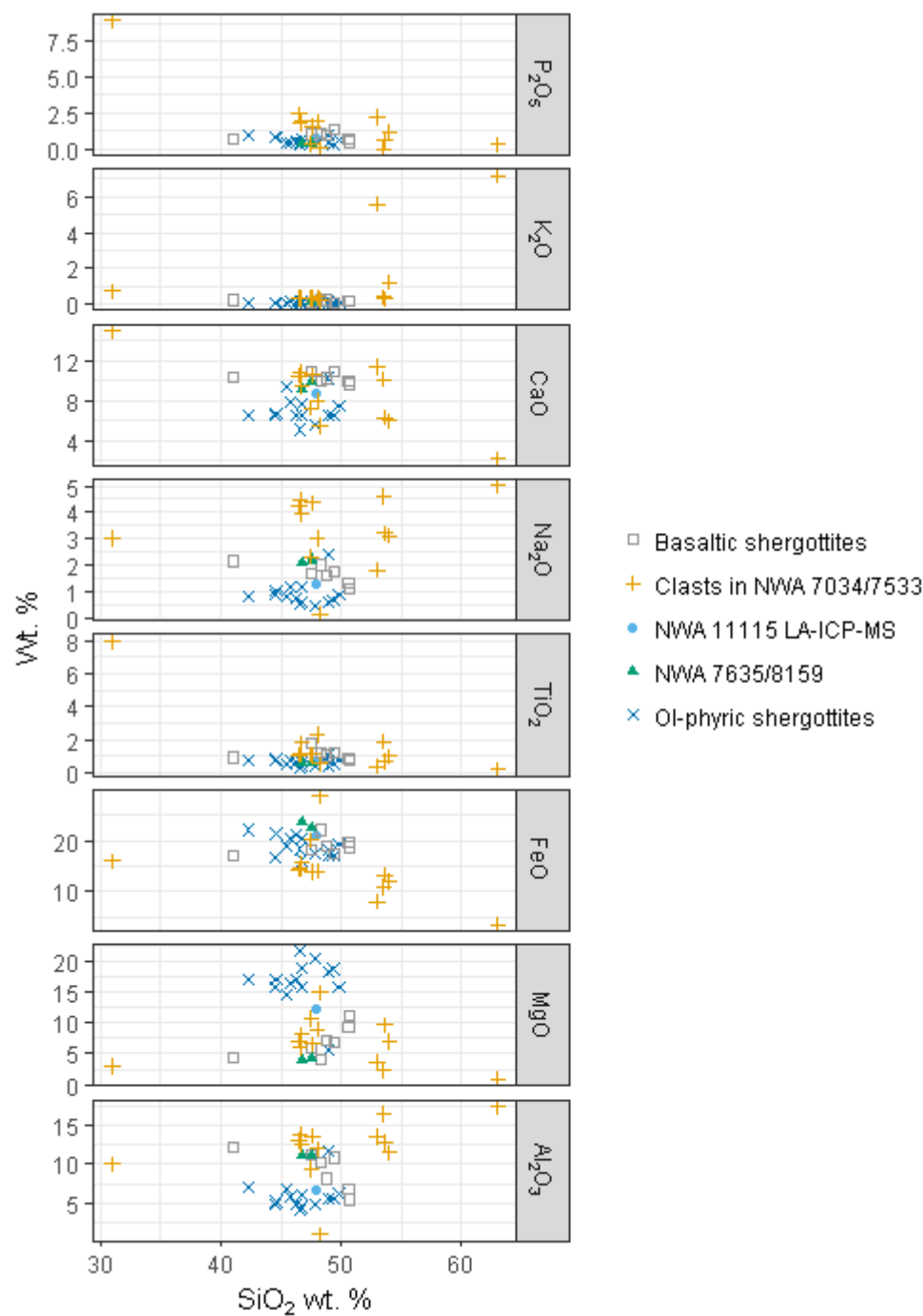
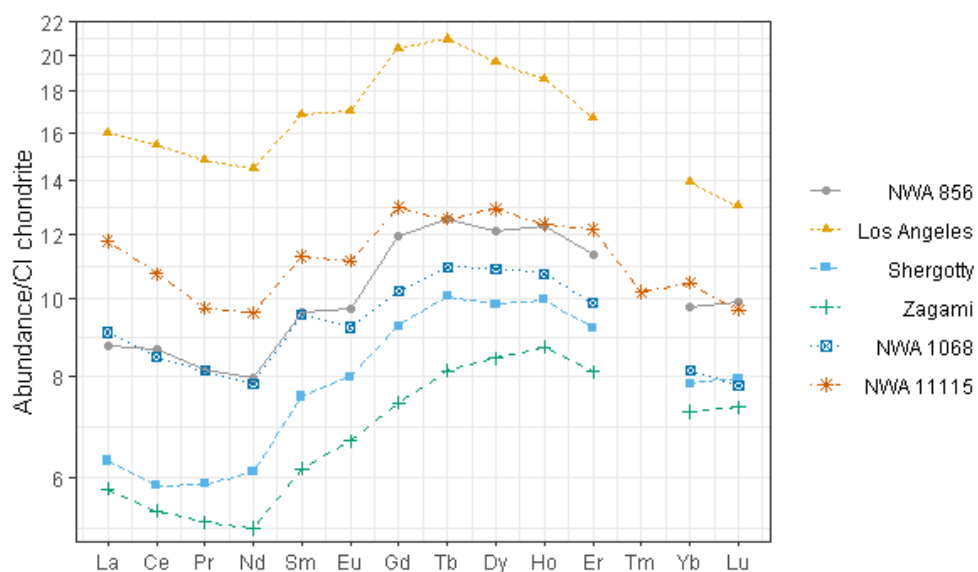


Figure 6. Harker diagram of major oxides in the bulk compositions of martian meteorites. Data for other meteorites are from the compilation by Filiberto (2017).

264



265

Figure 7. Rare earth element concentrations in enriched martian meteorites normalized to concentrations in CI chondrites. Data for CI chondrites are from the reported CI chondrite mean composition in Dauphas and Pourmand (2015), data for Shergotty and Zagami are from Barrat et al. (2001), and data for NWA 856 and Los Angeles are from the ICP-MS results by Jambon et al. (2002).

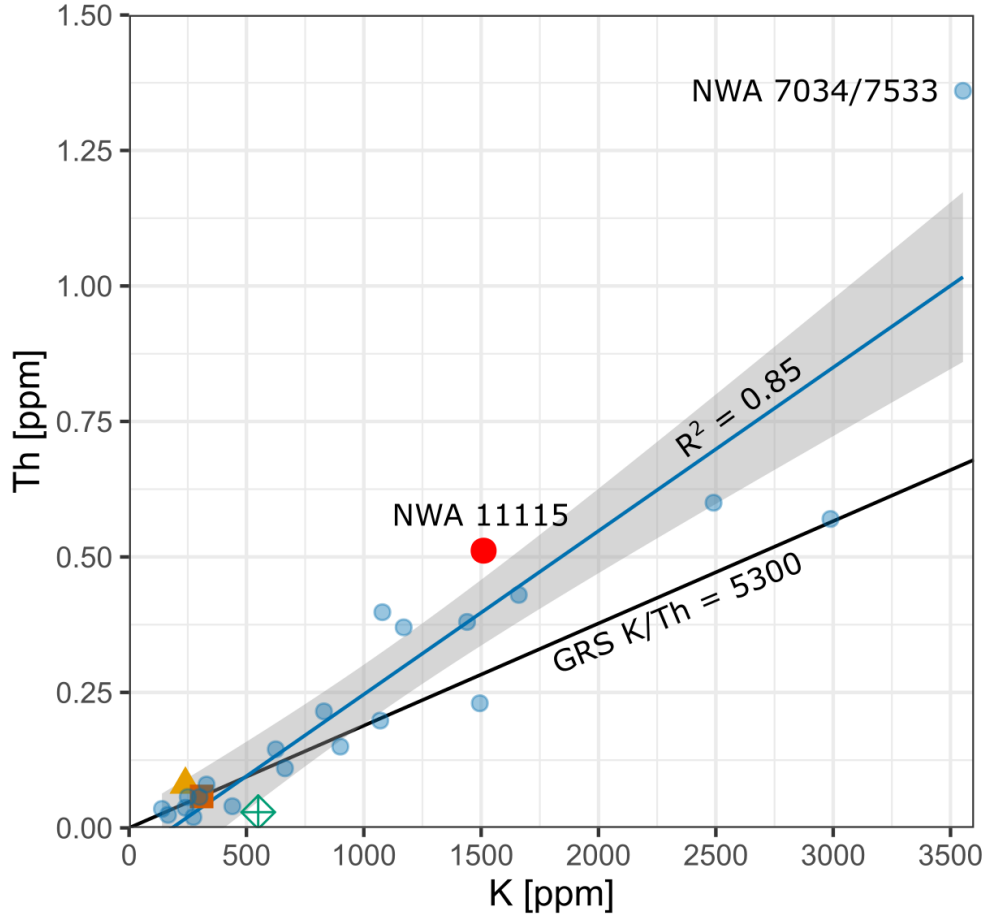


Figure 8. Comparison of K vs. Th concentration in NWA 11115 (red point), other martian meteorites (blue points), CI chondrites (green crossed diamond), bulk silicate Mars (orange square), bulk silicate Earth (yellow triangle) and Mars Odyssey's Gamma Ray Spectrometer measurements of the martian surface (black trend line). The blue line is a linear regression between all martian meteorites on the plot, apart from NWA 11115, and the grey area marks the 95 % confidence interval. Data for the martian meteorites apart from NWA 11115 are from the compilation by Filiberto (2017), CI chondrite data and bulk silicate Earth data are from McDonough and Sun (1995), and bulk silicate Mars is from Taylor (2013).

269 3.2. Oxygen isotopes

270 Laser-assisted fluorination of two aliquots of NWA 11115 gave an average isotopic composition of:
 271 $\delta^{17}\text{O} = +2.823 \pm 0.017(2\sigma) \text{ ‰}$, $\delta^{18}\text{O} = +4.796 \pm 0.072(2\sigma) \text{ ‰}$, and $\Delta^{17}\text{O} = 0.329 \pm 0.021(2\sigma) \text{ ‰}$ (where
 272 $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$). The data for NWA 11115 are shown in relation to other martian meteorites
 273 analyzed by laser fluorination (Fig. 6). The average $\Delta^{17}\text{O}$ of these martian samples is 0.307 ‰, i.e., slightly
 274 lower than the value obtained for NWA 11115 (Figure 9). However, the mean martian $\Delta^{17}\text{O}$ value of Franchi
 275 et al. (1999) is 0.321, i.e., closer to the value for NWA 1115. Thus, the oxygen isotope composition of NWA
 276 11115 is consistent with it being a martian sample.

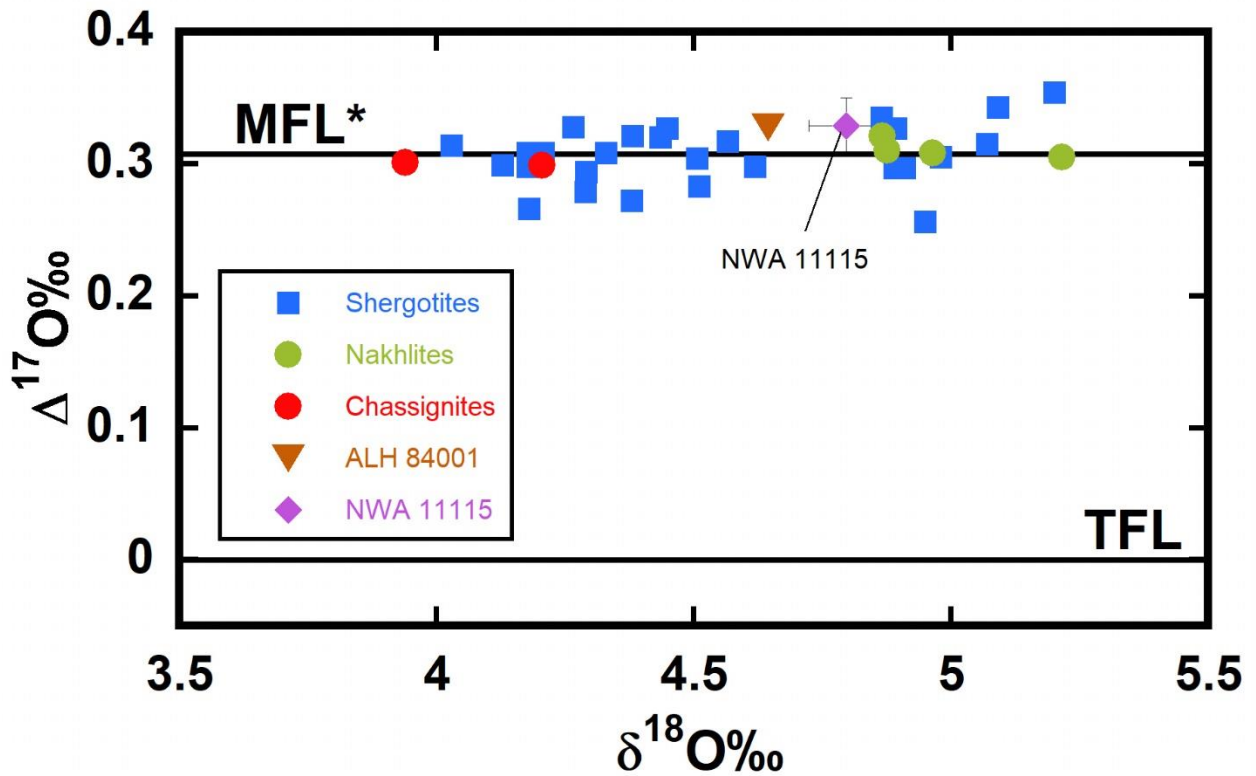


Figure 9. Oxygen isotope composition of NWA 11115 (error bars 2σ) and other martian meteorites analyzed by laser fluorination. MFL* is the mean $\Delta^{17}\text{O}$ of all the samples plotted in Fig. 6 with the exception of NWA 11115 and has a value of 0.307. TFL is the terrestrial fractionation line. Data: Franchi et al. (1999) and Meteoritical Bulletin Database oxygen isotope analyses for Tissint, DaG 478, DaG 670, JaH 479, LAR 06319, NWA 1669, NWA 2737, NWA 4222, NWA 5718, NWA 5790, NWA 6162, NWA 7032, NWA 7042, SaU 094, Y-000027, Y-000047, Y-000097.

4. DISCUSSION

Concentrations of elements between martian meteorites can be compared to understand the provenance and the relationship between martian rocks. Bulk element mass ratios of NWA 11115 (Fe/Mn, Na/Al, etc.) are typical of other martian meteorites, and more specifically shergottites (Table 6) although the whole-rock K/Th ratio (~ 2987) is significantly lower than the average surface of Mars (Taylor et al. 2006) and is also on the lower end compared to other martian meteorites (Figure 8).

Table 6. Element mass ratios used for provenance tests. Martian meteorite average ratios from Taylor (2013) unless otherwise noted.

Sample-UniBern		Martian meteorite mean	
Ratio	$\pm 2\sigma$	Ratio	$\pm 2\sigma$
Martian meteorite tests			

Fe/Mn	41.4	1.7	40.3	2.3
Ni ppm/Mg wt. %	18.649	2.465	17.946	Nd
K/Th	2987	810	5300 ^a	220 ^a
P/Yb	1802.14	211.60	2065.27	Nd
Ga ppm/Al wt. %	4.284	0.625	4.067	Nd
Na/Al	0.278	0.015	0.247	Nd
MgO wt. %/Cu ppm	0.812	0.242	0.611	Nd
Shergottite tests				
Rb/La	2.3822	1.0451	2.9066	Nd
Rb/K	0.0045	0.0012	0.0047	Nd
Cs/La	0.1613	0.0781	0.1805	Nd
Weathering tests				
Th/U	4.09	0.77	>0.2 (unweathered) <0.2 (weathered)	
Sr/Nd	12.26	3.53		
Ce/Ce ^{*b}	1.01	0.04	< 1 (leached) > 1 (oxidized or enriched)	
K/La	526.94	154.59		

^aGlobal surface average from the Gamma Ray Spectrometer on Mars Odyssey (Taylor et al. 2006).

^bCI chondrite Ce abundance from Dauphas and Pourmand (2015).

4.1. Provenance on Mars

The relationship between Ti and K concentrations in martian meteorites and surface rocks on Mars has previously been used to discern between processes that affected the rocks on the path to crystallization, as well as post-crystallization processes such as metasomatism (e.g. Treiman and Filiberto, 2015; Filiberto, 2017). Similarly, the relationship of bulk MgO vs. bulk Al₂O₃ also tracks the degree of igneous crystallization and accumulation processes, since earlier crystallizing phases (forsteritic olivine, Mg-pyroxene) tend to be richer in magnesium and poorer in aluminum, whereas later crystallizing phases (plagioclase feldspar) follow the opposite trend (e.g. Filiberto, 2017). NWA 11115 is somewhat closer to the olivine-phyric shergottites in its Ti vs. K relationship (Figure 10), but on the other hand, it is more in line with the basaltic shergottites, when comparing the relationship between MgO and Al₂O₃ (Figure 11). From these relationships, we would assume that NWA 11115 crystallized relatively early on and did not experience much igneous fractionation (increasing Al₂O₃) or mantle metasomatism (increasing K; Schmidt et al. 2014). However, this is at odds with the moderately high bulk SiO₂ content (Figure 6 and Table 5), the large modal abundance of plagioclase feldspar within NWA 11115, as well as abundant phosphates, which typically form later in the crystallization sequence. Additionally, the highly enriched REE nature of the sample also appears to preclude early crystallization, unless the mantle source of NWA 11115 was especially REE-enriched.

Overall, the petrography and major element geochemistry closely resemble those of NWA 1068. NWA 1068 is an olivine-phyric shergottite with a similar modal mineralogy, petrography and bulk geochemistry (Barrat et al. 2002; Filiberto et al. 2010). The only significant differences between the meteorites appear to be the slightly higher SiO₂ and lower MgO content of NWA 11115 (SiO₂ = 45.78 wt. % and MgO ≈ 16.64 wt. % for NWA 1068), which can be accounted for by the decreased olivine modal abundance in NWA 11115 relative to NWA 1068 (~14 % vs ~22%, Barrat et al. 2002). We note, however, that the bulk SiO₂ concentration was not reported for NWA 1068 by Barrat et al. (2002), but estimated by Filiberto et al. (2010). Thus, the petrologic experiments by Filiberto et al. (2010) for NWA 1068 apply to NWA 11115 also: all the olivine in the meteorite are likely to be settled cumulate crystals, and NWA 11115 probably originated in the same magmatic event close to, or slightly above the NWA 1068 in the cumulate pile, which would be consistent with the somewhat more REE-enriched chemistry and differences in modal mineralogy.

The analyzed melt pockets are intriguing in that their compositions consistently undersample the plagioclase composition of NWA 11115: while the meteorite is composed of ~ 30 vol. % maskelynite, the melt pockets appear to be composed of < 10 wt. % maskelynite (as is apparent from the low Al₂O₃; Table 4) and > 66 wt. % pyroxene (Table 4), which, even accounting for the lower density of plagioclase relative to pyroxene, is a significant mismatch. In addition, the melting temperature of plagioclase is lower than that of pyroxene, so the plagioclase composition should form a larger mass fraction of the melt pockets, unless shock melting is favored by frictional heating along the grain boundaries of the large phenocrysts, i.e. olivine and pyroxene. Frictional heating as the main mechanism for melt production would be consistent with the feathered texture along olivine and pyroxene grains where melt pockets are found.

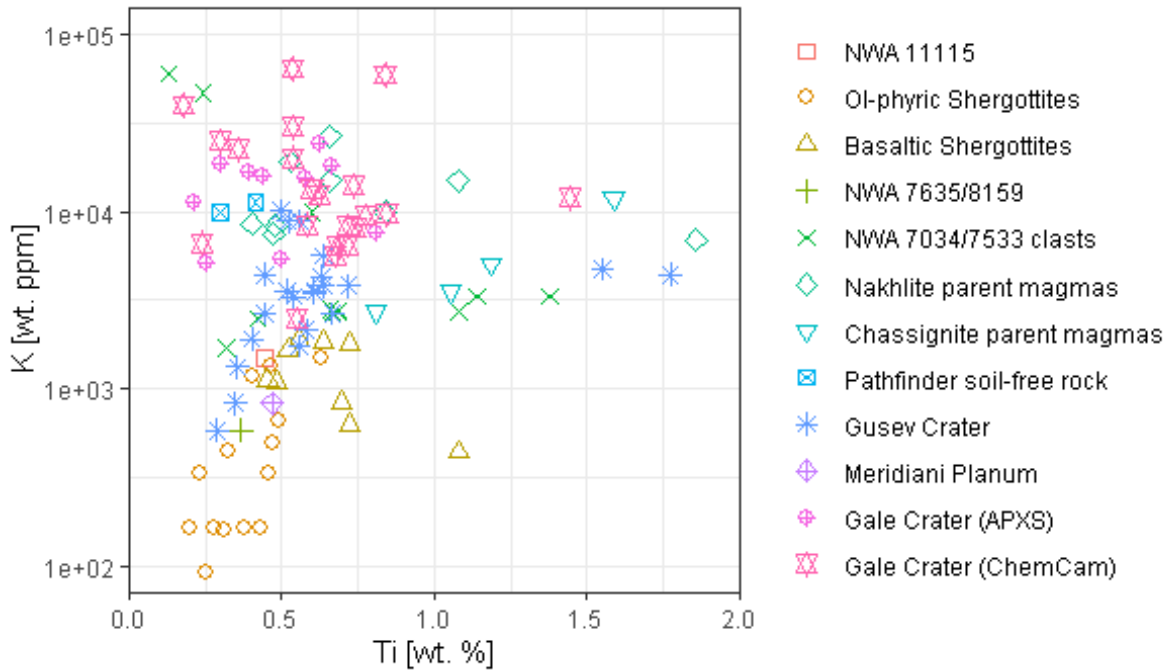
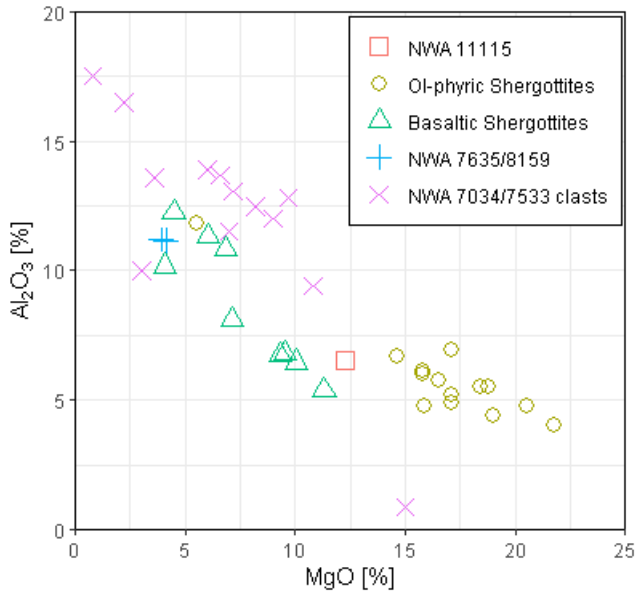


Figure 10. Semilog graph of bulk Ti concentration (wt. %) vs. bulk K concentration (wt. ppm). Data adapted from Filiberto (2017), with new data for NWA 11115. A data point from a Fe-Ti-P-rich clast of NWA 7034 is not plotted, as it contains high Ti concentration and lies far from the center of the graph.

327



328

Figure 11. Bulk MgO wt. % vs. bulk Al_2O_3 wt. % in NWA 11115 and other martian meteorites. Data for meteorites other than NWA 11115 are from the compilation by Filiberto (2017).

329

330 4.2. Terrestrial weathering

331 Bulk Th/U, Sr/Nd, and K/La mass ratios are often used as proxies for the degree of weathering meteorites
 332 experienced during their residence on Earth (e.g. Barrat et al. 2001; Taylor 2013; Taylor et al. 2002), measuring
 333 the relative excess of aqueously mobile versus immobile elements. Preferential depletion or enrichment of
 334 cerium is also a common result of terrestrial weathering in meteorites (Croaz et al. 2003; e.g. Floss and Croaz
 335 1991, 1993), which either causes the removal of Ce^{3+} by dissolution of REE-rich phases (e.g. Ca-phosphates),
 336 or oxidizes the relatively soluble Ce^{3+} to relatively insoluble Ce^{4+} , thereby enriching Ce in the sample relative
 337 to REEs with similar masses (La and Pr). We quantify Ce concentration anomalies, by calculating the “Ce/Ce*”
 338 ratio as in Dauphas and Pourmand (2015):

$$\frac{\text{Ce}}{\text{Ce}^*} = \frac{\text{Ce}_N}{\text{La}_N^{0.48} \times \text{Pr}_N^{0.52}} \quad (1)$$

339 where Ce_N , La_N , and Pr_N are the concentrations of these REE elements in the sample normalized to the
 340 concentrations of these in CI chondrites. (We use the CI chondrite values reported in Dauphas and Pourmand
 341 (2015).)

342 By these measures, NWA 11115 is, if at all, only slightly affected by terrestrial weathering: the Th/U ratio is
 343 near-chondritic, the relatively high Sr is tracked by high Nd, and the Ce/Ce* ratio is close to 1 (Table 6). In
 344 addition, the bulk oxygen isotopes place the meteorite far from the terrestrial fractionation line (Figure 9).
 345 However, the meteorite clearly contains an abundance of large fractures infilled with calcite (e.g. Figure 2) and

other secondary phases, so the discrepancy is puzzling. A possible explanation is that the alteration was largely isochemical, requiring only atmospheric water to react with the mineral phases in the meteorite to form the alteration phases, the positive and negative Ce anomalies balance out, and the absence of a terrestrial oxygen signature could be attributed to the preparation procedure of the sample for laser-assisted fluorination. This is an unsatisfying explanation, however, because the CO₂ required to form the carbonates was likely atmospheric, and not indigenous to the meteorite. We note that abundant martian carbonates are found in the Allan Hills 84001 meteorite and some nakhlite meteorites (e.g. Lafayette, Nakhla, Governador Valadares, e.g. Bridges et al., 2019). However, we argue that the alteration phases are likely terrestrial because the calcite-filled fractures cross-cut the fusion crust (see CT scan in the electronic appendix). Future targeted analyses of the carbon isotopes in the calcite could more conclusively determine their origin.

5. CONCLUSIONS

NWA 11115 is an enriched olivine-phyric shergottite with some unusual properties, but is otherwise petrographically and geochemically similar to NWA 1068, albeit with a higher concentration of SiO₂ as a result of higher maskelynite modal abundance at the expense of cumulate olivine crystals. The bulk K/Th ratio of NWA 11115 is low (K/Th $\approx$ 2987) compared to other martian meteorites (Figure 8), and the surface of Mars (K/Th $\approx$ 5300 (Taylor et al. 2006)). This could be related to fractional crystallization, as in some Zagami lithologies (McCoy et al. 1999). However, the K abundance is not especially low compared to other martian meteorites. Instead, NWA 11115 is Th enriched. Most likely, the large phosphate crystals are the hosts of the Th (as well as U, also relatively enriched). We recommend further analyses of the phosphate minerals, which we also suspect are the main hosts of the REE. Given the similarity of NWA 1068 with NWA 11115, we suggest that these meteorites are genetically linked, with NWA 11115 somewhat higher up in the cumulate pile suggested by its higher REE-enrichment, and the differences in modal mineralogy mentioned above. In addition, the analyzed melt pockets in NWA 11115 are intriguing because their compositions undersample the abundant maskelynite in the meteorite (Table 4). Finally, while NWA 11115 is likely altered, as evidenced by the abundant fracture-filling calcite, trace element proxies for alteration (e.g. Sr/Nd) do not correlate with other martian meteorites known to have experienced hot desert alteration (e.g. Dhofar 019 and Dar al Gani 476/489; see Folco et al. 2000; Taylor et al. 2002). Further analyses of the alteration mineralogy are an area of interest to understand its provenance and effects on the geochemistry of the meteorite.

Data Availability

All data are available in the Supplementary Information file, and at the following Zotero link: [\[DOI and link to be made live after review\]](#).

Acknowledgements

The authors acknowledge T. Boudreaux for donating NWA 11115 to the Field Museum, J. Greer and J. Holstein for help with sample preparation, L. Kööp and B. Strack for SEM support, S. Rastegar for preliminary SEM

analysis, L. Dussubieux for LA-ICP-MS support, A. I. Neander and Z.-X. Luo for μ CT scanning and support, and J. Filiberto and A. Treiman for useful discussions. We thank Thomas Pettke for assistance with LA-ICP-MS analyzes of the pressed powder pellets at the University of Bern. GPS Division analytical facilities at Caltech and Chi Ma are thanked for the support on EMPA analysis. PRH acknowledges support from the Tawani Foundation. MMD's portion of the work was done partly as a private venture and not in the author's capacity as an employee of the Jet Propulsion Laboratory, California Institute of Technology. The authors declare no competing interests.

References

- Agee C. B. et al. 2013. Unique Meteorite from Early Amazonian Mars: Water-Rich Basaltic Breccia Northwest Africa 7034. *Science* 339:780–785.
- Barrat J. A., Blichert-Toft J., Nesbitt R. W., and Keller F. 2001. Bulk chemistry of Saharan shergottite Dar al Gani 476. *Meteoritics & Planetary Science* 36:23–29.
- Barrat J. A., Jambon A., Bohn M., Gillet P. h, Sautter V., Göpel C., Lesourd M., and Keller F. 2002. Petrology and chemistry of the Picritic Shergottite North West Africa 1068 (NWA 1068). *Geochimica et Cosmochimica Acta* 66:3505–3518.
- Borg L. E., and Draper D. S. 2003. A petrogenetic model for the origin and compositional variation of the martian basaltic meteorites. *Meteoritics & Planetary Science* 38:1713–1731.
- Bridges J. C., Hicks L. J., and Treiman A. H. 2019. Chapter 5 - Carbonates on Mars. In *Volatiles in the Martian Crust*, edited by Filiberto J., and Schwenzer S. P. Elsevier. pp. 89–118
<http://www.sciencedirect.com/science/article/pii/B9780128041918000052>.
- Crozaz G., Floss C., and Wadhwa M. 2003. Chemical alteration and REE mobilization in meteorites from hot and cold deserts. *A Special Issue Dedicated to Robert M Walker* 67:4727–4741.
- Dauphas N., and Pourmand A. 2015. Thulium anomalies and rare earth element patterns in meteorites and Earth: Nebular fractionation and the nugget effect. *Geochimica et Cosmochimica Acta* 163:234–261.
- Droop G. T. R. 1987. A general equation for estimating Fe³⁺ concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineralogical Magazine* 51:431–435.
- Ferracutti G. R., Gargiulo M. F., Ganuza M. L., Bjerg E. A., and Castro S. M. 2015. Determination of the spinel group end-members based on electron microprobe analyses. *Mineralogy and Petrology* 109:153–160.
- Filiberto J., Musselwhite D. S., Gross J., Burgess K., LE L., and TREIMAN A. H. 2010. Experimental petrology, crystallization history, and parental magma characteristics of olivine-phyric shergottite NWA 1068: Implications for the petrogenesis of “enriched” olivine-phyric shergottites. *Meteoritics & Planetary Science* 45:1258–1270.
- Filiberto J., and Dasgupta R. 2011. Fe²⁺–Mg partitioning between olivine and basaltic melts: Applications to genesis of olivine-phyric shergottites and conditions of melting in the Martian interior. *Earth and Planetary Science Letters* 304:527–537.
- Filiberto J., Gross J., Trela J., and Ferré E. C. 2014. Gabbroic Shergottite Northwest Africa 6963: An intrusive sample of Mars. *American Mineralogist* 99:601.

- 424 Filiberto J. 2017. Geochemistry of Martian basalts with constraints on magma genesis. *Chemical Geology*
425 466:1–14.
- 426 Floss C., and Crozaz G. 1991. Ce anomalies in the LEW85300 eucrite: evidence for REE mobilization
427 during Antarctic weathering. *Earth and Planetary Science Letters* 107:13–24.
- 428 Floss C., and Crozaz G. 1993. Heterogeneous REE patterns in oldhamite from aubrites: Their nature and
429 origin. *Geochimica et Cosmochimica Acta* 57:4039–4057.
- 430 Folco L., Franchi I. A., D’Orazio M., Rocchi S., and Schultz L. 2000. A new martian meteorite from the
431 Sahara: The shergottite Dar al Gani 489. *Meteoritics & Planetary Science* 35:827–839.
- 432 Franchi I. A., Wright I. P., Sexton A. S., and Pillinger C. T. 1999. The oxygen-isotopic composition of Earth
433 and Mars. *Meteoritics & Planetary Science* 34:657–661.
- 434 Goodrich C. A. 2002. Olivine-phyric martian basalts: A new type of shergottite. *Meteoritics & Planetary*
435 *Science* 37:B31–B34.
- 436 Greenwood R. C., Burbine T. H., Miller M. F., and Franchi Ian. A. 2017. Melting and differentiation of early-
437 formed asteroids: The perspective from high precision oxygen isotope studies. *Geochemistry* 77:1–
438 43.
- 439 Gross J., Filiberto J., Herd C. D. K., Melwani Daswani M., Schwenzer S. P., and Treiman A. H. 2013.
440 Petrography, mineral chemistry, and crystallization history of olivine-phyric shergottite NWA 6234:
441 A new melt composition. *Meteoritics & Planetary Science* 48:854–871.
- 442 Humayun M. et al. 2013. Origin and age of the earliest Martian crust from meteorite NWA 7533. *Nature*
443 503:513–516.
- 444 Irving A. J. 2021. An up-to-date List of Martian Meteorites. <https://imca.cc/mars/martian-meteorites-list.htm>
445 (Accessed May 28, 2021).
- 446 Jambon A., Barrat J. A., Sautter V., Gillet Ph., Göpel C., Javoy M., Joron J. L., and Lesourd M. 2002. The
447 basaltic shergottite Northwest Africa 856: Petrology and chemistry. *Meteoritics & Planetary Science*
448 37:1147–1164.
- 449 McCoy T. J., Wadhwa M., and Keil K. 1999. New lithologies in the Zagami meteorite: evidence for
450 fractional crystallization of a single magma unit on Mars. *Geochimica et Cosmochimica Acta*
451 63:1249–1262.
- 452 McDonough W. F., and Sun S. -s. 1995. The composition of the Earth. *Chemical Evolution of the Mantle*
453 120:223–253.
- 454 McSween H. Y. 1994. What we have learned about Mars from SNC meteorites. *Meteoritics* 29:757–779.
- 455 Melwani Daswani M., Heck P. R., Greber N. D., and Greenwood R. C. 2017. Petrography and Geochemistry
456 of Northwest Africa 11115: A New, Enriched, High Thorium Basaltic Shergottite. In *80th Annual*
457 *Meeting of the Meteoritical Society*. p. 6302.
- 458 Miller M. F., Franchi I. A., Sexton A. S., and Pillinger C. T. 1999. High precision $\delta^{17}\text{O}$ isotope
459 measurements of oxygen from silicates and other oxides: method and applications. *Rapid*
460 *Communications in Mass Spectrometry* 13:1211–1217.
- 461 Papike J. J., Karner J. M., Shearer C. K., and Burger P. V. 2009. Silicate mineralogy of martian meteorites.
462 *Geochimica et Cosmochimica Acta* 73:7443–7485.
- 463 Peters D., and Pettke T. 2017. Evaluation of Major to Ultra Trace Element Bulk Rock Chemical Analysis of

464 Nanoparticulate Pressed Powder Pellets by LA-ICP-MS. *Geostandards and Geoanalytical Research*
465 41:5–28.

466 Santos A. R., Agee C. B., McCubbin F. M., Shearer C. K., Burger P. V., Tartèse R., and Anand M. 2015.
467 Petrology of igneous clasts in Northwest Africa 7034: Implications for the petrologic diversity of the
468 martian crust. *Geochimica et Cosmochimica Acta* 157:56–85.

469 Schindelin J. et al. 2012. Fiji: an open-source platform for biological-image analysis. *Nature Methods* 9:676–
470 682.

471 Schmidt M. E. et al. 2014. Geochemical diversity in first rocks examined by the Curiosity Rover in Gale
472 Crater: Evidence for and significance of an alkali and volatile-rich igneous source. *Journal of*
473 *Geophysical Research: Planets* 119:64–81.

474 Starkey N. A. et al. 2016. Triple oxygen isotopic composition of the high- $^3\text{He}/^4\text{He}$ mantle. *Geochimica et*
475 *Cosmochimica Acta* 176:227–238.

476 Taylor L. A. et al. 2002. Martian meteorite Dhofar 019: A new shergottite. *Meteoritics & Planetary Science*
477 37:1107–1128.

478 Taylor G. J. et al. 2006. Variations in K/Th on Mars. *Journal of Geophysical Research: Planets* 111:E03S06.

479 Taylor G. J. 2013. The bulk composition of Mars. *Chemie der Erde - Geochemistry* 73:401–420.

480 The Meteoritical Society. 2017. *Meteoritical Bulletin 106*, Lunar and Planetary Institute
481 <https://www.lpi.usra.edu/meteor/> (Accessed August 28, 2018).

482 Treiman A. H. 1996. The perils of partition: Difficulties in retrieving magma compositions from chemically
483 equilibrated basaltic meteorites. *Geochimica et Cosmochimica Acta* 60:147–155.

484 Treiman A. H., and Filiberto J. 2015. Geochemical diversity of shergottite basalts: Mixing and fractionation,
485 and their relation to Mars surface basalts. *Meteoritics & Planetary Science* 50:632–648.

486 Usui T., McSween H. Y., and Floss C. 2008. Petrogenesis of olivine-phyric shergottite Yamato 980459,
487 revisited. *Geochimica et Cosmochimica Acta* 72:1711–1730.

488 Wittmann A., Korotev R. L., Jolliff B. L., Irving A. J., Moser D. E., Barker I., and Rumble D. 2015.
489 Petrography and composition of Martian regolith breccia meteorite Northwest Africa 7475.
490 *Meteoritics & Planetary Science* 50:326–352.

491

1 Comparison between previously reported bulk chemistry data and superseding new analyses

A chip of NWA 11115 (*Sample-FMNH*) was homogenized by using an agate mortar and pestle, yielding approximately 31 mg of powder. The powder was fluxed with LiBO₂ and fused and quenched into five glass beads. The beads were mounted in an epoxy on one sample holder and polished. NIST Standard Reference Materials (SRM) 610 and 612 were used for measurement calibration. NIST SRM 610 followed by two blanks was used for bracketing unknowns. We carried out a total of 24 repeat analyses of the sample. Data were reduced using the SILLIS software (Guillong et al. 2008).

The bulk composition of *Sample FMNH* was analyzed at the Field Museum of Natural History (Chicago) using Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS). The LA-ICP-MS setup at the Field Museum's Elemental Analysis Facility is a ThermoFisher Scientific iCAP Qc Quadrupole ICP-MS Spectrometer coupled to a New Wave UP213 UV laser ablation system. For this study a laser aperture resulting in a 100 µm spot size was used.

The LA-ICP-MS analyses carried out at the FMNH resulted in some anomalous values, some of which (including previously unknown K/Th ratios for the martian meteorites and surface) were reported in Melwani Daswani et al. (2017). Because some dubious element abundances were obtained, we carried out electron probe microanalyses (EPMA) of the glass sample prepared for the FMNH to test its compositional homogeneity and whether the unusual analyses were caused by the instrument. EPMA analyses confirmed that the K concentration of the sample was low, but there were significant differences in the concentrations of other elements (Supplementary Table 1).

The EMPA analysis of FMNH-beats were performed using a JEOL 8200 electron microprobe (WDS: 15 kV; 5 nA; beam defocused to 20 µm) interfaced with the Probe for EPMA program from Probe Software, Inc. Standards for these analyses were synthetic fayalite (FeK α), Shankland forsterite (MgK α), synthetic Mn₂SiO₄ (MnK α), synthetic anorthite (AlK α , SiK α , CaK α), Amelia albite (NaK α), Asbestos microcline (KK α), synthetic TiO₂ (TiK α), and synthetic Cr₂O₃ (CrK α). Quantitative elemental microanalyses were processed with the CITZAF correction procedure (Armstrong 1995). Nominal ~85% percent of LiBO₂ is added in Probe Software to correct for matrix effect and achieve near 100% oxide wt% total. The LiBO₂ was later excluded for reporting the composition of FMNH-beats (supplementary Table 1).

As a result of the discrepancies between the analytical results of the same sample, and the unusual element mass ratios (especially the low relative potassium: K/Th, K/La), we performed a separate LA-ICP-MS analysis at the University of Bern (*Sample-UniBern*), which is described in the Main Text, and we include the calibration measurements and 27 spot analyses in the Supplementary Spreadsheet File S1. In addition, we back-calculated the bulk rock chemistry from the modal mineralogy, and obtained a composition that was significantly closer to *Sample-UniBern* (calculations shown in Supplementary Spreadsheet File S1, and summarized results shown in Supplementary Table 3). Thus, we consider that the results from *Sample-UniBern* supersede the *Sample-FMNH* analyses.

Supplementary Table 1. Whole rock chemistry of two samples of NWA 1115. Oxides are reported in wt. %, and individual elements in µg/g.

	Sample-FMNH						Sample-UniBern		
	LA-ICP-MS			EPMA Caltech			LA-ICP-MS		
	n	Mean	±2σ	n	Mean	±2σ	n	Mean	±2σ
SiO ₂	24	52.56	2.78	8	44.74	1.09	27	47.90	1.09
TiO ₂	24	0.96	0.03	8	0.45	0.75	27	0.74	0.28
Al ₂ O ₃	24	8.08	1.00	8	10.16	0.87	27	6.53	0.97
FeO _T	24	16.27	4.25	8	22.32	1.72	27	20.97	1.43
MnO	24	0.50	0.03	8	0.72	0.41	27	0.51	0.03
MgO	23	8.72	1.14	8	11.36	0.84	27	12.27	0.74
CaO	24	10.15	1.39	8	8.66	0.45	27	8.67	0.48
Na ₂ O	24	0.84	0.13	8	0.66	0.25	27	1.30	0.18
K ₂ O	24	0.03	0.02	8	0.02	0.05	27	0.18	0.04
P ₂ O ₅	20	0.78	0.02				27	0.73	0.21
Li							27	4.34	0.50
Be	16	0.78	0.39				27	0.37	0.15
B							27	3.66	0.98
Cl	18	415.54	313.22						
Sc	20	52.04	1.22				27	44.69	4.23
V	24	244.17	19.23				27	232.17	41.30
Cr	24	2555.65	200.91	8	2188.82	742.72	27	2348.05	1560.64
Co	24	45.83	4.13				27	47.00	4.04
Ni	24	143.14	30.72				27	138.03	20.90
Cu	20	28.67	31.77				27	15.44	4.62
Zn	20	42.32	8.69				27	91.22	13.44
Ga	20	15.21	1.22				27	14.79	2.52
Ge							27	0.80	0.12
As	24	bdl ^a	nd ^b				27	0.19	0.04
Rb	22	2.35	7.26				27	6.86	2.91
Sr	24	77.31	6.72				27	56.13	6.77
Y	24	19.04	2.01				27	17.55	5.46
Zr	24	79.15	9.11				27	57.27	22.97
Nb	24	5.29	0.60				27	3.84	1.80
Mo	24	3.28	0.66				27	0.13	0.04
Ag	4	0.26	0.24				27	0.01	0.01
Cd	12	0.36	0.72				26	0.04	0.02
In							27	0.03	0.01
Sn	23	0.71	0.95				27	0.30	0.08
Sb	17	0.72	0.88				21	0.01	0.01
Cs	22	0.28	0.50				27	0.46	0.22
Ba	20	110.09	5.52				27	62.47	7.77
La	20	4.16	0.53				27	2.92	1.00
Ce	23	6.64	1.18				27	6.82	2.45
Pr	24	1.06	0.36				27	0.94	0.35
Nd	24	4.81	0.74				27	4.68	1.70
Sm	24	1.92	0.42				27	1.76	0.63
Eu	23	0.82	0.27				27	0.67	0.20
Gd	24	2.96	0.65				27	2.72	0.97
Tb	23	0.64	0.29				27	0.48	0.15

Rb/La	0.54	1.70	-	-	2.38	1.05	2.9066	Nd
Rb/K	0.01	0.03	-	-	0.005	0.001	0.0047	Nd
Cs/La	0.07	0.11	-	-	0.16	0.08	0.1805	Nd
Weathering tests								
Th/U	2.05	1.91	-	-	4.09	0.77		
Sr/Nd	16.13	2.34	-	-	12.26	3.53		
Ce/Ce ^{*b}	0.78	0.12	-	-	1.01	0.04		
K/La	57.92	25.57	-	-	526.94	154.59		

^aGlobal surface average from the Gamma Ray Spectrometer on Mars Odyssey (Taylor et al. 2006).

Supplementary Table 3. Back-calculation of the bulk chemical composition of NWA 11115 from the modal mineralogy, using the mean mineral compositions determined using spot analyses with the BSE SEM (see main text). Densities to derive the mass from the mode were obtained from the Handbook of Mineralogy (Anthony et al.). Since minor sulfide and silica phases were not analyzed, they are assumed to be pyrite and quartz for the purposes of recalculating the bulk composition. Slight discrepancies in the sum totals are due to rounding errors. Detailed calculation is found in the Supplementary Spreadsheet File S1.

	Olivine	Clinopyroxene	Plagioclase	FeCrMnMgAl Ti oxides	Sulfides	Phosphates	Silica	Total wt. %
Normalized mode	14.36	50.60	30.62	1.91	0.30	2.11	0.10	100
Normalized mass	16.85	52.86	25.14	2.66	0.46	1.95	0.08	100
SiO ₂	5.84	27.27	14.03	0.01	nd	nd	0.08	47.24
TiO ₂	nd	0.12	bdl	0.04	nd	nd	nd	0.16
Al ₂ O ₃	nd	0.81	6.81	0.18	nd	<0.01	nd	7.81
Cr ₂ O ₃	nd	0.21	nd	1.43	nd	nd	nd	1.64
FeO _T	6.91	11.07	0.19	0.88	0.14	0.05	nd	19.23
MnO	0.13	0.36	nd	0.02	nd	nd	nd	0.51
MgO	3.83	9.83	0.05	0.08	nd	nd	nd	13.79

CaO	0.04	2.78	2.49	<0.01	nd	1.03	nd	6.35
Na ₂ O	nd	bdl	1.36	nd	nd	0.03	nd	1.39
K ₂ O	nd	nd	0.09	nd	nd	nd	nd	0.09
P	0.01	bdl	nd	nd	nd	0.91	nd	0.92
S	0.01	0.03	nd	nd	0.09	<0.01	nd	0.13

References

- Anthony J. W., Bideaux R. A., Bladh K. W., and Nichols M. C. Handbook of Mineralogy. *Handbook of Mineralogy*. <http://handbookofmineralogy.org/> (Accessed July 25, 2021).
- Armstrong J. T. 1995. CITZAF: A package of correction programs for the quantitative Electron Microbeam X-Ray-Analysis of thick polished materials, thin-films, and particles. *Microbeam Analysis* 4:177–200.
- Guillong M., Meier D. L., Allan M. M., Heinrich C. A., and Yardley B. W. 2008. Appendix A6: SILLS: A MATLAB-based program for the reduction of laser ablation ICP-MS data of homogeneous materials and inclusions. *Mineralogical Association of Canada Short Course* 40:328–333.
- Melwani Daswani M., Heck P. R., Greber N. D., and Greenwood R. C. 2017. Petrography and Geochemistry of Northwest Africa 11115: A New, Enriched, High Thorium Basaltic Shergottite. In *80th Annual Meeting of the Meteoritical Society*. p. 6302.
- Taylor G. J. et al. 2006. Variations in K/Th on Mars. *Journal of Geophysical Research: Planets* 111:E03S06.
- Taylor G. J. 2013. The bulk composition of Mars. *Chemie der Erde - Geochemistry* 73:401–420.