PETROLOGIC, ELEMENTAL AND MULTI-ISOTOPIC CHARACTERIZATION OF PERMAFIC OLIVINE-PHYRIC SHERGOTTITE NORTHWEST AFRICA 5789: A PRIMITIVE MAGMA DERIVED FROM DEPLETED MARTIAN MANTLE. A. J. Irving[1], S. M. Kuehner[1], C. D. K. Herd[2], M. Gellissen[3], R. L. Korotev[4], I. Puchtel[5], R. J. Walker[5], T. J. Lapen[6] and D. Rumble, III[7] [1]Earth & Space Sciences, University of Washington, Seattle, WA 98195 (irving@ess.washington.edu), [2]Earth & Atmospheric Sciences, University of Alberta, Edmonton, AB, [3]Institut für Geologie, Ruhr-Universität Bochum, Germany, [4]Earth & Planetary Sciences, Washington University, St. Louis, MO, [5]Dept. of Geology, University of Maryland, College Park, MD, [6]Earth & Environmental Sciences, University of Houston, TX, [7]Geophysical Laboratory, Carnegie Institution, Washington, DC.

A fresh 49 gram achondrite meteorite coated by black fusion crust found in Morocco in 2009 is a very primitive olivine-phyric Martian igneous rock similar in many respects to Yamato 980459/980497 [1].

Figure 1. *Three interlocking, fusion-crusted pieces of Northwest Africa 5789. Photo © S. Ralew.*

Figure 2. *Endcut fragment, showing yellow-green olivine grains in a pale brownish-gray pigeonite-rich groundmass. Scale cube is 1 cm. Photo © S. Ralew.*

Petrography: The specimen is composed of small (up to 1 mm), clustered, pale yellowish-green olivine macrocrysts (25 vol.%; zoned from cores as magnesian as $Fa_{15.6}$ to thin $Fa_{45.4}$ rims; FeO/MnO = 45.2-58.9) set in finer grained groundmass of mainly prismatic pyroxene grains (70 vol.%), with accessory chromite [(Cr/(Cr+Al) = 0.880], pyrrhotite, and ~2 vol.% mesostasis regions composed of subparallel, laminar intergrowths of pigeonite, plagioclase ($An_{60.0-62.5}Or_{0.5-0.6}$, ***not*** maskelynite), silica, ilmenite and merrillite. Pyroxenes are zoned from cores of orthopyroxene ($Fs_{17.1-17.8}Wo_{1.6}$,) to pigeonite ($Fs_{25.6}Wo_{9.8}$,), augite ($Fs_{25.3}Wo_{25.0}$,) and ferropigeonite rims ($Fs_{78.9}Wo_{16.5}$); FeO/MnO = 26.8-31.3. Magmatic oxygen fugacity was calculated using the Ol-Px-Sp method from compositions of Mg-rich orthopyroxene cores, equilibrium olivine and earliest formed chromite (with highest Cr#, lowest Fe#), yielding a log fO_2 of IW + 0.2 ± 0.2 (n=5).

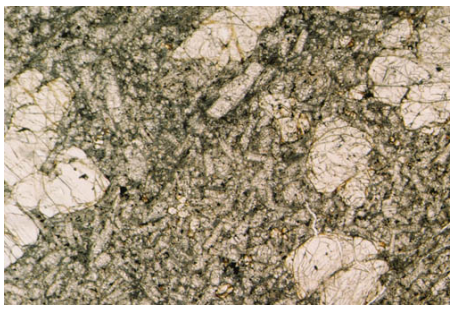


Figure 3. *Plane polarized light image (9 mm) showing olivine glomerocrysts in a pigeonite-rich groundmass*

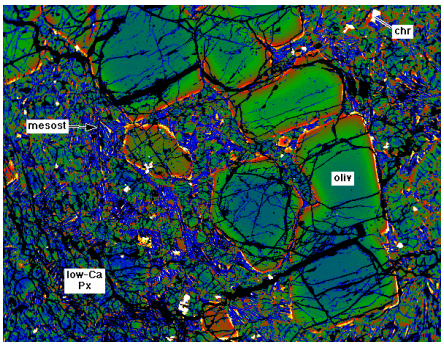
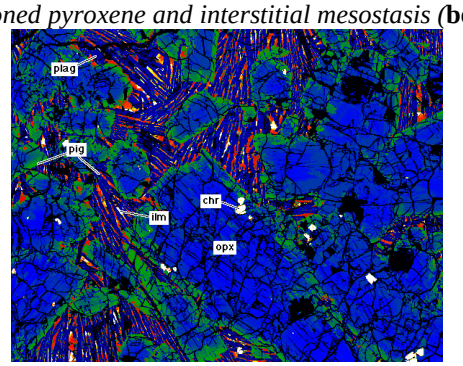


Figure 4. *BSE images, showing zoned olivine glomerocrysts and pigeonite-rich groundmass (***above***) and zoned pyroxene and interstitial mesostasis (***below***)*

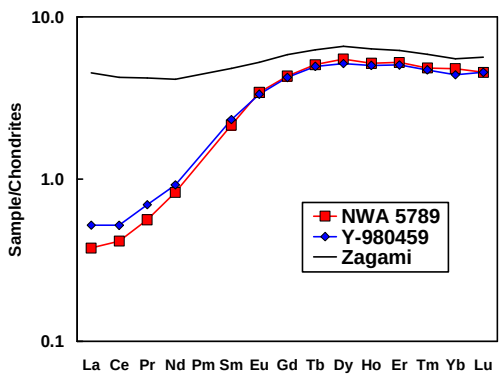


Oxygen Isotopes: Analyses of two acid-washed whole rock subsamples by laser fluorination gave, respectively: $\delta^{18}O$ = 4.60, 4.52; $\delta^{17}O$ = 2.64, 2.66; $\Delta^{17}O$ = 0.216, 0.278 per mil. The dispersion in values is similar to that found for many other shergottites [2].

Bulk Elemental Composition: Powder from a representative 1.9 gram whole interior slice was analyzed by XRF, INAA, ICP-MS and TIMS.

	NWA 5789	*Yamato 980459* [3]		*NWA 5789*	*Yamato 980459*
SiO_2	48.57	49.3	La	0.12	0.166
TiO_2	0.45	0.54	Ce	0.34	0.426
Al_2O_3	5.33	5.22	Pr	0.068	0.084
Cr_2O_3	0.73	0.70	Nd	0.51	0.667
FeO_T	17.56	17.42	Sm	0.43	0.466
MnO	0.45	0.50	Eu	0.26	0.254
MgO	19.15	19.17	Gd	1.15	1.13
CaO	6.53	6.60	Tb	0.25	0.244
Na_2O	0.69	0.67	Dy	1.81	1.7
K_2O	0.02	0.02	Ho	0.39	0.379
P_2O_5	0.34	0.29	Er	1.13	1.09
SUM	99.94	100.43	Tm	0.159	0.155
Mg/(Mg+Fe)	0.660	0.662	Yb	1.06	0.971
Other NWA 5789 abundances:			Lu	0.15	0.15

Sc 35.1, V 210, Co 52.6, Ni 210, Hf 0.49, Rb 0.33, Sr 24.9 ppm; Pt 1.6, Os 5.4 ppb



Nomenclature: In order to place the nomenclature of shergottites on a more systematic basis, we propose that bulk major element parameters such as CaO content and Mg/(Mg+Fe) ratio be used, in addition to textural and trace element/isotopic characteristics (see Figure 6). In this scheme, those specimens formerly called "lherzolitic" shergottites (except NWA 1950) become ultramafic poikilitic shergottites. RBT 04262 and NWA 4468 are enriched permafic poikilitic shergottites, and those rocks called "basaltic" shergottites become mafic (or diabasic) shergottites (variously with enriched, depleted or intermediate isotopic ratios). NWA 5789 is a depleted permafic olivine-phyric shergottite compositionally very similar to Yamato 980459 [3]. Other permafic olivine-phyric shergottites have enriched (NWA 1068) or intermediate (EET 79001A) signatures; NWA 2990 and 5960 (paired) are fine grained, enriched mafic olivine-phyric shergottites.

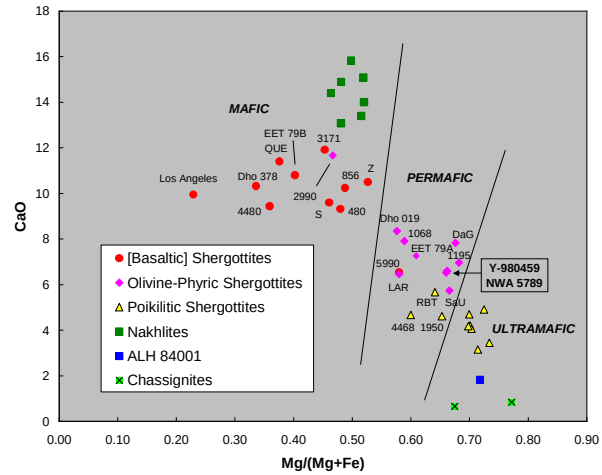


Figure 6. *Proposed bulk chemical classification of Martian igneous rocks. Boundary lines are arbitrary.*

Neodymium Isotopes: TIMS analysis of the whole rock powder gave $^{143}Nd/^{144}Nd$ = 0.515297 ± 8, or a modern day ε_{Nd} value of +51.89. If the age is within the range for other shergottites (~150-580 Ma), then this Nd isotopic ratio is consistent with a long-term depleted source similar to that of Yamato 980459 [5].

Highly Siderophile Elements and Osmium Isotopes: Bulk HSE abundances are similar to those for ultramafic shergottites, but the present day $^{187}Os/^{188}Os$ ratio is more radiogenic (0.163). Given its subchondritic $^{187}Re/^{188}Os$ ratio, NWA 5789 must reflect a mantle source with long-term suprachondritic Re/Os, or else substantial contamination with crust. By comparison, HSE abundances in Yamato 980459 are 3-4 times higher, yet $^{187}Os/^{188}Os$ is lower (0.130), so these two meteorites differ considerably in HSE characteristics.

Discussion: NWA 5789 is a very primitive Martian magmatic rock, but olivine in equilibrium with the bulk composition should be $Fa_{14.5}$ (i.e., 1 mole% less ferroan than the observed macrocysts). Other depleted shergottites (e.g., DaG 476, SaU 005, NWA 1195) show this same effect, but with even more ferroan olivine core compositions (Fa_{19-29}). We conclude that, except for rapidly quenched Yamato 980459, early-formed olivine in shergottites was variably modified by reaction with magmatic liquids as a function of cooling rate. Some of these specimens may be launch-paired.

References: [1] Greshake A. et al. (2004) *GCA* **68**, 2359-2377; Mikouchi T. et al. (2004) *Ant. Met. Res.* **17**, 13-34 [2] Rumble D. and Irving A. (2009) *Lunar Planet. Sci.* **XL**, #1480 [3] Shirai N. and Ebihara M. (2004) *Ant. Met. Res.* **17**, 55-67; Misawa K. (2004) *Ant. Met. Res.* **17**, 1-12. [5] Shih C.-Y. et al. (2005) *Ant. Met. Res.* **18**, 46-65.

Website: http://www.imca.cc/mars/martian-meteorites.htm