NORTHWEST AFRICA 773: LUNAR MARE BRECCIA WITH A SHALLOW-FORMED OLIVINE-CUMULATE COMPONENT, VERY-LOW-TI HERITAGE, AND A KREEP CONNECTION. B. L. Jolliff, R. L. Korotev, R. A. Zeigler, C. Floss, and L. A. Haskin; Department of Earth and Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130. blj@levee.wustl.edu.

Introduction: Northwest Africa 773 is one of the more unusual lunar meteorites found in recent years because it contains a prominent clast lithology, which appears to be an olivine-rich cumulate [1-4] and because it is a very-low-Ti (VLT) mare breccia with relatively high incompatible-trace-element concentrations and LREE/HREE enrichment [3]. A lunar origin was verified by Fagan and coworkers [2] on the basis of noble-gas contents, oxygen isotopes, and mineral compositions. Fagan et al. described two lithologies: (1) heterolithic impact breccia with a regolith component and (2) cumulus olivine gabbronorite. Here, we refer to these as the breccia (Bx) lithology and the olivine-cumulate (OC) lithology.

The impact breccia components are predominantly volcanic (basaltic), and, in this context, the occurrence of the cumulus lithology is especially significant: is it related to the volcanic components or does it represent a deep-seated rock entrained by the basaltic magma as it rose to the surface? Elevated incompatible-element concentrations with more or less KREEP-like inter-element ratios and very-low-Ti concentrations distinguish both lithologies of this meteorite from Apollo mare basalts. Here, we summarize key compositional information (bulk and mineral), especially related to the OC lithology, to show that it formed at shallow depth and comes from a VLT ultramafic precursor that mixed with a KREEP-like trace-element component deep in the crust or upper mantle.

Description: Samples that we have studied contain about ⅔ basaltic breccia matrix and ⅓ coarse-grained olivine-gabbro cumulate. The breccia matrix contains small lithic and mineral clasts of OC, and Bx matrix extends into fractures in large clasts of OC. The OC lithology is about half olivine, 35–40% pigeonite+augite, and 10% plagioclase (Tables 1,2). Because of coarse grain size and small samples, modes reported by [2-4] vary significantly. The low plagioclase content puts the assemblage right at the boundary between olivine gab- bro and lherzolite, but the small size of most fragments makes this distinction academic. Clearly, the assemblage has excess (cumulus) olivine and pyroxene. The Bx matrix contains a variety of basaltic debris including clasts of OC minerals, zoned pyroxene, olivine, and plagioclase grains; ferroan symplectites; and small lithic clasts of fine-grained basalt and granophyre. One coarse (>1 mm) plagioclase clast of basaltic affinity (An_{95}, 0.6% FeO+MgO) suggests that plagioclase accumulation complementary to OC may have occurred in the target area of NWA773.

Table 1. NWA773 Breccia and OC compositions

	Breccia Matrix FB-EMPA	Olivine Cumulate FB-EMPA	OC Parent Eq RM + 40% Ol	A14 Green Avg A&B [5,9]
SiO_2	46.2	44.8	44.53	44.62
TiO_2	0.78	0.24	0.59	0.71
Al_2O_3	10.6	3.1	7.05	6.88
Cr_2O_3	0.40	0.39	0.20	0.53
FeO	17.3	18.1	20.7	20.8
MnO	0.26	0.27	0.26	0.30
MgO	13.2	27.1	18.2	17.6
CaO	10.8	6.01	8.28	8.03
Na_2O	0.23	0.03	0.22	0.16
K_2O	0.10	0.02	0.04	0.02
P_2O_5	0.09	0.05		
Mg/(Mg+Fe)	0.58	0.73	0.61	0.60
Ca/Al molar	1.8	3.5	2.1	2.1

FB-EMPA: compositions determined by electron-microprobe analysis of multiple fused beads; Na_2O in OC by this method is partially volatolized (INAA yields 0.13 wt%). OC parent calculated as equilibrium residual melt (calculated using parameterizations of Longhi) plus 40% olivine.

The olivine-gabbro lithology exhibits cumulus textures and, in our largest section of it, includes some 48% olivine (Fo_{67}), 28% pigeonite ($En_{63}Fs_{25}Wo_{12}$), 12% augite ($En_{49}Fs_{14}Wo_{37}$), 2% hypersthene ($En_{70}Fs_{26}Wo_4$), 10% plagioclase (An_{80-94}), and trace barian K-feldspar, ilmenite, RE-merrillite, troilite, and chromite. The Mg/Fe ratios of the mafic silicates indicate equilibration of Fe and Mg; however, plagioclase retains compositional variations consistent with intercumulus crystallization. Accessory mineralogy reflects crystallization of late-stage residual melt. Both lithologies (breccia and olivine cumulate) of the meteorite have very-low-Ti (VLT) compositions and share a unique trace-element signature, i.e., relatively enriched in light REE and large-ion-lithophile elements and more depleted in Eu than almost all other known lunar volcanic rocks.

Mineralogy of OC: Pyroxene and olivine are well equilibrated in Mg' but pyroxene grains span a range in Wo for both pigeonite and augite. CaO concentrations of olivine average 0.17 wt% (0.11-0.26), which is on the low end of the range typical of olivine in mare basalts, but greater than found in lunar nonmare intrusive rocks [5]. Wollastonite contents of pyroxene are consistent with accumulation between 1200-1100°C and solidification of intercumulus melt by 1050°C at low pressure. Pigeonite grains are very finely exsolved, typically submicron (Fig. 1). Plagioclase in OC is zoned from An_{94} to An_{80}, consistent with solidification mainly from trapped melt. FeO (0.20-0.65 wt%) and MgO (0.10-0.16 wt%) are significantly higher than typical of lunar intrusive rocks. In summary, mineral compositions and fine pyroxene exsolution textures indicate shallow crystallization.

Table 2. Modal mineralogy of the OC lithology

	MR[1]	mineral composition (this work)			FB Norm[2]
	vol%	average	*Mg'*	range	vol%
Olivine	48	$Fo_{67.5}$	67.5	*Mg'* 63-69	48.2
Pigeonite	27	$En_{53}Wo_{12}$	71.6	*Mg'* 71-72	27.0[3]
Augite	11	$En_{49}Wo_{37}$	77	*Mg'* 74-79	12.9[3]
Hypersthene	2	$En_{70}Wo_{4}$	72		
Plagioclase	11	$An_{88}Ab_{10}Or_{2}$		An 80-94	10.8
K-Feldspar	tr	$Or_{92}Ab_{4}An_{2}Cn_{2}$			0.17
Ilmenite	tr				0.33
RE-Merrillite	tr				0.12

[1]MR: optimized from modal recombination/petrographic image analysis.
[2]FB Norm: normative mineralogy from fused-bead analyses, OC lithology.
[3]Pyroxene values for FB Norm recast as pigeonite and augite of measured Wo content. [4]Mg' = Mg/(Mg+Fe) atomic × 100. We also observed troilite, Cr-spinel in OC, and Fe-Ni metal.

The concentrations of REE in silicates in OC measured by ion microprobe indicate crystallization from an REE-enriched melt. Using pigeonite, augite, and plagioclase with the lowest measured REE concentrations, and distribution coefficients from [6], we calculate an equilibrium melt at about 0.6 × KREEP at La and Ce to about 0.25 × KREEP at Yb and Lu (Fig. 2), i.e., KREEP-like but with a significantly steeper LREE to HREE slope.

Terrestrial contamination: NWA773 shows signs of exposure to the terrestrial environment. As is evident in Fig. 1, calcite fills fractures throughout the meteorite. However, of seven ion probe analyses of pyroxene, only one showed a positive Ce anomaly. In that grain, which also has elevated Sr and Ba concentrations, the ion probe spot intersected a carbonate veinlet, which probably accounts for the observed contamination. We also note LREE enrichment in olivine and some pyroxene analyses, which may be attributed to terrestrial contamination [e.g., 7]. These measurements are not used for petrogenetic interpretations. The bulk meteorite composition, however, does not have a significant positive Ce anomaly, and the alteration present does not appear to affect interpretations about petrogenesis.

Petrology: Using parameterizations from Longhi [8], we calculated a melt composition that would produce the observed assemblage Ol+Pig+Aug+Pl. Addition of 40% olivine to this composition produces a close match to the composition of VLT picritic glass from Apollo 14, specifically Green Glass B, Type 1 (Table 1 [9]). This particular glass composition is noteworthy because it has high REE concentrations and LREE/HREE slope for a lunar picritic glass [5,9]. It also has exceptionally low Eu, a distinguishing characteristic of NWA773 (both lithologies).

We postulate that the parent melt of NWA773 OC was similar to A14GGBT1, but that it had very low concentrations of incompatible elements. The melt incorporated a KREEP-like (but steeper LREE/HREE) component in transit from the mantle to the surface. The melt ponded near the surface, accumulated olivine for an extended period, and then Ca-rich pyroxene (pigeonite followed shortly by augite). The OC assemblage and composition is consistent with retention of some 15–25% intercumulus liquid as trapped melt. Eruption and tapping of variably differentiated melt during crystallization produced surface basaltic components that are similar to those now found in the brecciated matrix of NWA773. The KREEP-like pattern of incompatible-element contents coupled with an olivine-rich and magnesian precursor suggests a link to magnesian-suite igneous rocks [see also 4] and to the mafic-end (volcanic) components of EET87/96 [10]. The relatively young age suggested by Ar-Ar dating [11] and relative incompatible-element enrichment is consistent with an origin in a region characterized by extended volcanic activity such as in a low-Ti region of the Procellarum KREEP Terrane, perhaps at the site of origin of the green volcanic glasses found in Apollo 14 soil.

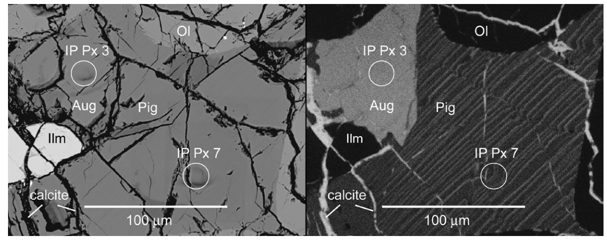

Figure 1. Backscattered-electron (left) and Ca X-ray images of pyroxene in NWA773 OC. Exsolution in pigeonite is the coarsest seen in our section. Calcite deposits in fractures are common.

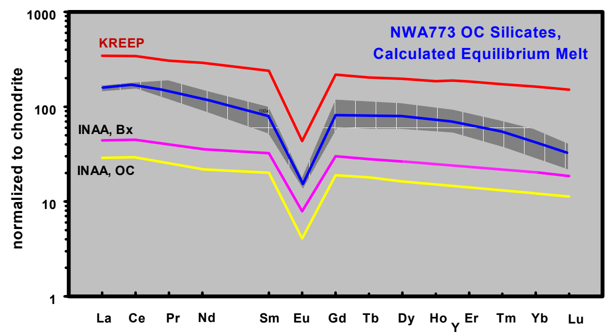

Figure 2. Blue: average melt in equilibrium with pyroxene and plagioclase with lowest REE concentrations in NWA773 OC; stippled field defined by plagioclase, pigeonite, and augite patterns.

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