AN OXYGEN ISOTOPE MIXING MODEL FOR THE NORTHWEST AFRICA 011 BASALTIC ACHONDRITE.
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Introduction: The eucrites lie on an oxygen isotopic mass fractionation line that is sub-parallel to the terrestrial fractionation line in the oxygen three isotope diagram. Several estimates of the eucrite parent body (EPB) composition have been made over the last few decades [1, 2, 3, 4 ,5, 6, 7, 8]. Parent body estimates try to approximate a bulk composition for the asteroid, so that when melted, magmas consistent with the compositions of the meteorite samples are generated. [5] were the first to do this based on oxygen isotopic constraints, as well as, petrologic and compositional factors. Within their model, different chondritic components were mixed in specific proportions so the final composition had an oxygen isotopic signature identical to the eucrites. The proportions were determined using the distances between the oxygen isotopic composition of the chondritic components and the eucrite fractionation line. Only binary models were tried but, more complex models involving three or more components could be employed, such as those done later by [8]. The only implicit requirement for such binary models is that the two components lie on opposite sides of the eucrite fractionation line, so that the final calculated composition equals the oxygen isotopic composition of the eucrites.

Recently, a new basaltic achondrite, Northwest Africa (NWA) 011, was found in the Sahara desert. It is a pigeonite-plagioclase basalt and was first identified as a eucrite, based solely on its petrology [9]. However, oxygen isotopic analysis and further study show that it is different from the eucrites and plots in a different region of the oxygen three isotope diagram [10]. The oxygen isotopic model of [5] will be applied to NWA 011 to determine a parent body composition of this unusual basaltic achondrite.

Petrology and Bulk Composition of NWA 011: Northwest Africa 011 is a basalt composed of large, millimeter-sized anhedral grains of pigeonite and relict augite, as well as fine grained (50-100 um), stubby to granular plagioclase. It contains the minor phases of ilmenite, Ti-rich chromite, Fe-rich olivine, silica minerals, calcium phosphate, baddeleyite (ZrO_2), troilite and some weathering products [10]. An unusual feature of NWA 011 is that its bulk composition is quite different from the eucrites and is depleted in silica and phosphate, while being enriched in FeO and TiO_2. The silica and phosphate depletions are thought to be the result of redistribution during high temperature metamorphism, since both these minerals often occur together as final products during crystallization. They are distributed very heterogeneously throughout the meteorite at the one centimeter scale.

Two bulk compositions have been published by [10] as supplementary material, one by wet chemistry and a second by INAA. Upon comparison, the two compositions did not match within error. Both the Fe/(Fe+Mg) and Fe/Mn were quite disparate. Contact with A. Yamaguchi (pers. comm., 2002) indicates sampling size was responsible for the mismatch, and that the wet chemistry was believed to be the more accurate bulk composition, however both compositions were plotted on the oliv-plag-silica pseudo-ternary by [12]. Eucrites plot on and around the peritectic point of the pseudo-ternary. Both compositions of NWA 011 plot below the opx-plag tie line, which should be impossible if it is a relatively simple basalt resulting from partial melting. They in fact plot very near the plagioclase-olivine phase boundary, resembling something similar to a lunar troctolite (a plagioclase-olivine rock containing little or no pyroxene). However [10] noted that both silica and phosphate are depleted in NWA 011 and these minerals are distributed very heterogeneously. This redistribution can easily account for the odd plot on the pseudo-ternary. It is the opinion of this author that NEITHER wet chemistry NOR INAA data are representative of the rock. Therefore, the bulk composition of NWA 011 was modified slightly to allow it to plot on the pseudo-ternary near the eucrites and reflect its mineralogy and texture. Between 1.2 and 4.4 wt% silica (SiO_2) was added back to either the INAA or wet chemistry bulk composition. It is likely, although not calculated for in Table 1, that ~0.25 wt% P_2O_5, in the form of phosphate, should also be added back into the bulk composition to balance out the severe depletion.

The basaltic texture and modified bulk composition is consistent with formation of NWA 011 similar to the eucrites, resulting from a partial melt undergoing slight fractionation during crystallization. Therefore, to produce a glass comparable to NWA 011 (or the eucrites), model compositions must plot in the olivine field to the left of a line tying the peritectic point to the olivine corner.

NWA 011 Parent Body Oxygen Isotope Mixing Model: Four compositions were calculated for the NWA 011 parent body by oxygen isotope mixing. Three compositions were determined mixing average enstatite chondrite with Allende (CV) or average H or LL chondrite with Allende. The mixing models assumed that the final proportions plot within one per mil of NWA 011 and remain on the NWA 011 fractionation line. The fourth composition was just the CR chondrite, Yamato 790112, as determined by [11]. Yamato 790112 plots slightly higher on the oxygen isotope diagram, but within analytical error of NWA 011. The four mixing models used are shown in Table 2 and Figure 1.

The H-Allende and LL-Allende compositions are actually quite similar to each other, while the CR composition is by far the most olivine normative of the four and the E-CO composition the richest in total iron. Sufficient iron metal was then removed (simulating core formation) to attain appropriate Fe/Mn ratios (55). Equilibrium olivine (simulating mantle formation) was fractionated until 100Fe/(Fe+Mg) ratios = 38. Bulk compositions with 100Fe/(Fe+Mg) ratios = 38 produce melts with ratios of 64 (NWA 011's FFM) (Table 3). It is assumed that during formation nearly all of the water is volatilized away.

Final Model Compositions: The compositions reveal that the H-Allende and LL-Allende models can produce compositions very close to the modified wet chemistry bulk of NWA 011. They have the appropriate Fe/Mn and FFM ratios as well as good CaO/Al_2O_3 ratios and SiO_2 abundance. The E-CO model is too SiO_2 rich, while being CaO and Al_2O_3 poor. This composition is actually consistent for diogenite genesis, but not a eucrite-like rock. The CR model, which was an obvious choice as a starting composition, actually produces the poorest result. The CaO/Al_2O_3 ratio is extremely high, while the SiO_2 is still too olivine normative. As in [5], an overabundance of the volatile elements (particularly Na_2O and K_2O) is present. A possible explanation concerning such overabundance is a large portion of the volatiles were lost to degassing during melting and differentiation of the parent asteroid.

In comparison to the EPB models of [5, 6, 7 and 8], the H-Allende and LL-Allende models for NWA 011 result in 1) a larger proportion of metal and much larger proportion of olivine being fractionated to the core and mantle in NWA 011 before the onset of equilibrium melting. 2) The proportion of sulfide and Ni in the core is lower than in the EPB.

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Table 1. NWA 011 Bulk

	Wet [1]	INAA [2]	Wet [3]	INAA [4]
SiO_2	45.76	47.41	48.04	48.03
TiO_2	0.92	0.79	0.88	0.78
Al_2O_3	13.16	11.64	12.61	11.51
Cr_2O_3	0.24	0.19	0.23	0.19
FeO	21.19	22.91	20.30	22.64
MnO	0.40	0.31	0.38	0.31
MgO	6.68	5.34	6.40	5.27
CaO	11.14	10.44	10.67	10.32
Na_2O	0.45	0.59	0.43	0.58
K_2O	0.03	0.05	0.03	0.05
P_2O_5	0.02	0.01	0.02	0.01
Fe/Mn	52.5	73.6	52.5	73.6
FFM[1]	64.0	84.7	64.0	84.7

1, 2, 3, 4 Columns 1 and 2 are wet chemistry and INAA from [10]. Columns 3 and 4 are re-normalized composition with the addition of SiO_2

Table 2. NWA 011 Parent Body Mixing Compositions

	40.2% H-59.8% All	34.9% LL-65.1% All	60.4% E-39.6% Isna	100% Y79
SiO_2	35.19	36.40	36.27	31.87
TiO_2	0.14	0.15	0.11	0.1
Al_2O_3	2.81	3.04	2.33	1.85
Cr_2O_3	0.52	0.51	0.36	0.51
FeO	20.44	23.68	10.13	32.07
MnO	0.23	0.24	0.21	0.25
MgO	24.07	24.89	22.05	23.16
CaO	2.26	2.38	1.40	2.11
Na_2O	0.61	0.61	0.76	0.28
K_2O	0.05	0.06	0.07	0.04
P_2O_5	0.25	0.23	0.24	0.23
FeS	4.56	4.49	7.93	3.56
Fe (metal)	6.43	1.05	13.40	0
Fe (total)	25.21	22.31	28.54	24.94
Ni	0.9	0.60	1.50	1.09
C	0.22	0.26	0.29	-
H_2O	0.83	0.56	1.30	3.80
Fe/Mn	141	118	173	128
FFM	43.6	39.3	48.3	43.7

Table 3. NWA 011 Parent Body Compositions after Metal and Olivine Removal

	H - Allende	LL -Allende	E – Isna	Y790112
SiO_2	47.42	46.59	52.02	44.57
TiO_2	0.29	0.29	0.23	0.22
Al_2O_3	5.96	5.97	4.89	3.98
Cr_2O_3	0.81	0.72	0.49	0.83
FeO	20.03	20.57	19.33	23.18
MnO	0.37	0.37	0.34	0.43
MgO	18.35	18.92	17.41	21.02
CaO	4.72	4.63	2.87	4.48
Na_2O	1.30	1.21	1.60	0.60
K_2O	0.10	0.11	0.15	0.09
P_2O_5	0.52	0.46	0.51	0.49
Fe/Mn	53.6	55.0	56.0	53.8
FFM[1]	38.0	37.9	38.4	38.2
% Fe (t) Removed[1]	61.6	53.2	67.6	59.7
% Eq. Oliv. Fract.[1]	40	38	37	37

[1] Removal of total Fe and equilibrium olivine (Fo90) from the bulk composition and then re-normalized to 100% for 11 oxides. Remainder of iron recast as FeO.