# PETROLOGIC, ELEMENTAL, ISOTOPIC AND MAGNETIC CHARACTERIZATION OF VESICULAR HYPABYSSAL ANGRITES NORTHWEST AFRICA 12004 AND NORTHWEST AFRICA 12320.

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**Introduction**: Since the witnessed fall of Angra dos Reis in 1869 a total of 19 additional distinct angrite specimens have been found, mostly in northwestern Africa. The two latest members of this very diverse class of achondrites both have diabasic igneous textures, and although similar do not seem to be terrestrially paired. Here we describe their petrology, mineralogy and bulk elemental compositions, as well as their oxygen-chromium-sulfur isotopic and magnetic characteristics.

**Northwest Africa 12004**: Found near Touignin, southern Morocco, this 183 gram sparsely vesicular specimen has a mean grainsize of 0.5 mm. Major minerals are zoned calcic olivine ($Fa_{36.6-84.1}Ln_{1.4-15.4}$, FeO/MnO = 70-95) with rims of kirschsteinite ($Fa_{62.4}Ln_{33.8}$, FeO/MnO = 69), zoned Al-Ti-augite ($Fs_{20.9-46.7}Wo_{52.0-52.9}$, FeO/MnO = 77-148, $TiO_2$ = 1.4-4.2 wt.%, $Al_2O_3$ = 7.3-11.6 wt.%) and anorthite ($An_{99.5-99.6}Ab_{0.3}Or_{0.0}$), accompanied by accessory titanomagnetite, troilite, silicoapatite and ferroan rhönite.

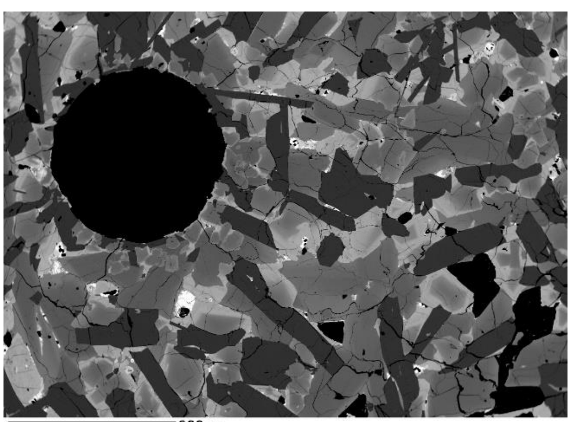


**Figure 1.** *BSE image of NWA 12004. Note the large vesicle with fine grained crystals on its outer rim.*

**Northwest Africa 12320**: This 4.5 kilogram meteorite found in several pieces in Mauritania is finer grained than NWA 12004, and contains sparse macrocrysts of magnesian olivine. It has a diabasic texture with some small vesicles containing partial interior coatings of secondary calcite and barite. Major minerals are zoned calcic olivine ($Fa_{39.6-79.7}Ln_{1.7-14.8}$, FeO/MnO = 72-96) with rims of kirschsteinite ($Fa_{57.9-63.3}Ln_{36.7-34.3}$, FeO/ MnO = 68-75), zoned Al-Ti-augite ($Fs_{20.5-45.9}Wo_{51.6-52.8}$, FeO/ MnO = 68-143, $TiO_2$ = 1.5-4.3 wt.%, $Al_2O_3$ = 6.9-7.8 wt.%) and anorthite ($An_{99.7}Ab_{0.2}Or_{0.0}$; with slightly more sodic rims $An_{96.6}Ab_{3.3}Or_{0.1}$), together with accessory titanomagnetite, troilite and silicoapatite. Olivine macrocrysts (possibly xenocrystic) have magnesian cores ($Fa_{13.8}Ln_{0.6}$) and more ferroan rims ($Fa_{35.2}Ln_{1.3}$; FeO/MnO = 85-103).

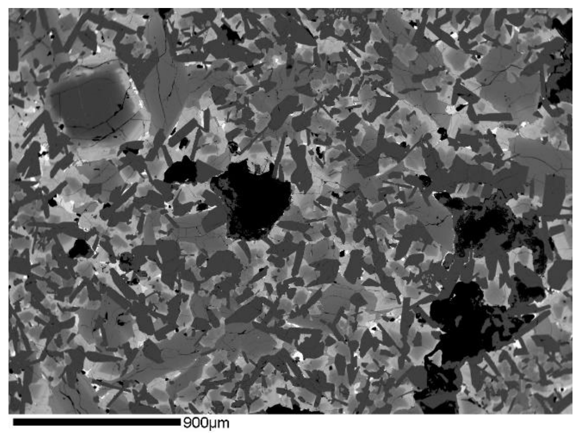


**Figure 2.** *BSE image of NWA 12320 at the same scale as for Figure 1. Note the olivine macrocryst with brighter ferroan rim (upper left) and vesicles (black).*

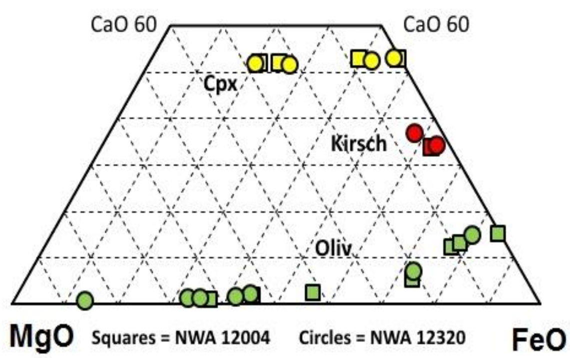


**Figure 3**. *Molar plot of pyroxene,olivine and kirschsteinite compositions in both specimens*

**Oxygen Isotopes**: Replicate analyses of acid-washed interior material by laser fluorination gave, respectively: for NWA 12004 $\delta^{17}O$ 2.258, 2.197, 2.285; $\delta^{18}O$ 4.440, 4.284, 4.431; $\Delta^{17}O$ -0.086, -0.065, -0.055; for NWA 12320 $\delta^{17}O$ 2.268, 2.281, 2.339; $\delta^{18}O$ 4.416, 4.407, 4.545; $\Delta^{17}O$ -0.063, -0.046, -0.060 (all per mil).

**Chromium Isotopes**: Analyses of both specimens at UC Davis yielded results plotted in Figure 4.

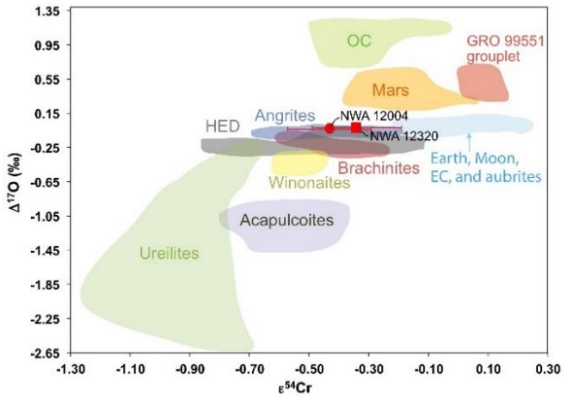


**Figure 4**. *Correlation of chromium and oxygen isotopic compositions for angrites and other "non-carbonaceous" meteorites, adapted from [1]*

**Bulk Major and Trace Elements**: Clean representative dust produced by cutting both samples on an Isomet saw were analyzed for major elements (in wt.%, by ICP-OES) and trace elements (in ppm, by QQQ-ICP-MS) at the University of Houston (Table 1). REE patterns (see Figure 5) are closely similar only to those for other diabasic and quenched angrites [2-4, unpub. data].

***Table 1. Whole Rock Elemental Abundances***

| | *12004* | *12320* | | *12004* | *12320* |
|---|---|---|---|---|---|
| $SiO_2$ | (40.1) | (40.4) | La | 3.64 | 3.31 |
| $TiO_2$ | 0.89 | 0.81 | Ce | 9.27 | 8.45 |
| $Al_2O_3$ | 11.74 | 11.83 | Pr | 1.39 | 1.26 |
| $Cr_2O_3$ | 0.05 | 0.05 | Nd | 6.86 | 6.20 |
| FeO | 24.98 | 24.27 | Sm | 2.17 | 1.98 |
| MnO | 0.27 | 0.26 | Eu | 0.85 | 0.78 |
| MgO | 6.32 | 6.65 | Gd | 2.95 | 2.67 |
| CaO | 14.96 | 15.15 | Tb | 0.50 | 0.46 |
| $Na_2O$ | 0.03 | 0.02 | Dy | 3.48 | 3.18 |
| $K_2O$ | 0.01 | 0.01 | Ho | 0.75 | 0.69 |
| $P_2O_5$ | 0.18 | 0.17 | Er | 2.19 | 2.02 |
| S | 0.43 | 0.42 | Yb | 2.07 | 1.92 |
| SUM | 100.0 | 100.0 | Lu | 0.311 | 0.287 |
| | | | Ba | 80.9 | 83.1 |
| *mg* | 0.311 | 0.328 | Rb | 0.29 | 0.13 |
| | | | Sr | 110 | 111 |

**Sulfur Isotopes**: Analyses at the University of Maryland yielded the following results for NWA 12004 and NWA 12320, respectively, normalized to Canyon Diablo troilite (CDT): $^{34}S$ -0.39‰, 0.11‰; $^{33}S$ 0.010‰, 0.010‰; $^{36}S$ -0.20‰, -0.21‰; S abundances 3096 ppm, 3318 ppm. These data are consistent with those reported for other angrites [5] showing sub per-mil variation of $^{34}S$, slightly positive $^{33}S$ and negative $^{36}S$ relative to CDT. The highly clustered signatures of $^{33}S$ and $^{36}S$ may reflect a homogeneous accretion of planetesimals with similar sulfur isotope signals, or instead large scale mixing of heterogenous accreted materials in the earliest accretion stage or during global magma generation.

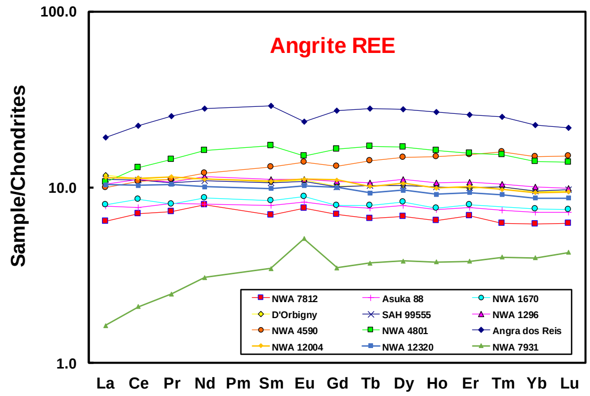


**Figure 5**. *Chondrite-normalized REE plot for angrites*

**Magnetic Paleointensity of NWA 12320**: Three-axis alternating field (AF) demagnetization of a 9.8 mg sample from the center of a 2 kg stone was followed by acquisition of anhysteretic remanent magnetization in a 50 μT bias field and further AF demagnetization. A low coercivity (<10 mT) component carries a viscous remanent magnetization (likely acquired from exposure to Earth's magnetic field), but there is no overprint from hand magnets, so that any other detectable fields should be from the solar nebula. The sample has no high coercivity (>10 mT) component, implying a null magnetic environment (0.3 ± 0.7 μT) at the time of last cooling, consistent with previous studies of only diabasic and quenched angrites [6, 7]. If NWA 12320 is as ancient as similar angrites, this would provide further evidence that the nebula had dissipated by 4 Myr after the time of formation of calcium-aluminum-rich inclusions.

**Concluding Remarks**: In many respects NWA 12004 and NWA 12320 resemble Sahara 99555 and D'Orbigny [2], and we interpret all to be hypabyssal igneous intrusions on the very ancient (and possibly long ago destroyed) angrite parent body (or bodies). Many questions remain: Why are these specimens vesicular? Why do only some angrites lack evidence for a dynamo magnetic field? How can their HSE abundances [3], W isotopes [8] and S isotopes [5] be reconciled with viable models? Why the unusually large range in cosmic ray exposure ages from <0.2 to 56 Myr [9]?

**References**: [1] Sanborn M. et al. (2019) *GCA* **245**, 577-596 [2] Mittlefehldt D. et al. (2002) *MaPS* **37**, 345-369 [3] Riches A. et al. (2012) *EPSL* **353-354**, 208-218 [4] Irving A. et al. (2013) *76th Meteorit. Soc Mtg.*, #5249 [5] Wu N. et al. (2018) *AGU Fall Mtg.*, #DI11B-0008 [6] Wang H. et al. (2017) *Science* **355**, 623-627 [7] Weiss B. et al. (2008) *Science* **322**, 713-716 [8] Kleine T. et al. (2012) *GCA* **84**, 186-203 [9] Nakashima D. et al. (2018) *MaPS* **53**, 952-972.