RARE EARTH ELEMENT GEOCHEMISTRY OF ANGRITE NORTHWEST AFRICA 2999.

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Introduction: The angrites are a small group of achondrites characterized by distinctive mineralogical and geochemical characteristics [1]. Most of the dozen or so currently known angrites belong to one of two textural subgroups: (1) relatively coarse-grained (slowly-cooled or "plutonic") angrites such as Angra dos Reis and LEW 86010, and (2) fine-grained (quickly cooled or "quenched") angrites such as D'Orbigny and Sahara 99555. These two textural subgroups have distinctly different Pb-Pb ages, with the plutonic angrites having ages ~6 Myr or so younger than the quenched angrites [2,3]. The angrite Northwest Africa 2999 is thought to represent an annealed breccia derived from a protolith with a coarse-grained texture similar to that of the plutonic angrites [4-6], but its modal mineralogy is different from that of other members of this subgroup. It is composed primarily of Ca-rich olivine (~64%) and Al,Ti-bearing diopside (~23%), along with metal (8%, the most of any known angrite), spinel (~4%), anorthite (~1%) and minor troilite [5]. It has an older Pb-Pb age than the plutonic angrites Angra dos Reis and LEW 86010 (although it is younger than the quenched angrites D'Orbigny and Sahara 99555) [7]. As such, it is unclear how NWA 2999 relates to the other known (plutonic and quenched) angrites. The goal of this investigation of rare earth element distributions in minerals of NWA 2999 is to understand the petrogenetic history of this unique angrite and its relationship to the other angrites.

Analytical Techniques: A polished thick section of NWA 2999 was characterized using a JEOL 8800 scanning electron microscope at Arizona State University (ASU). Major element abundances were analyzed in various mineral phases with an automated JEOL 8600 electron microprobe in ASU's Department of Chemistry and Biochemistry. Rare earth element (REE) concentrations were subsequently measured in selected minerals (clinopyroxenes, anorthite and olivine) using the Cameca IMS-6f ion microprobe at ASU, using methods similar to those described by [8].

Results and Discussion: Figures 1-3 show representative REE abundances in the various silicate minerals. The clinopyroxene grains analyzed so far show a relatively small range of REE concentrations (La ~5.4-6.4 × CI). Their REE patterns, characterized by LREE depletions and relatively flat HREE patterns, are most similar to those of clinopyroxenes in the quenched angrites (particularly, Sahara 99555) and distinct from the concave-downward REE patterns of clinopyroxenes in the plutonic angrite LEW 86010 (Fig. 1).

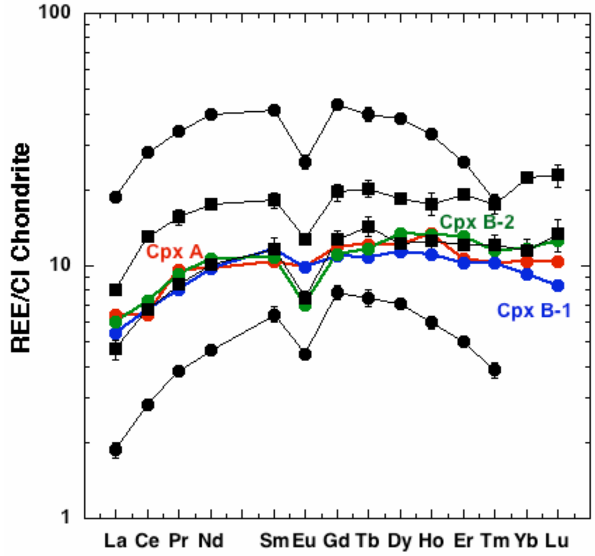

Figure 1. Representative REE abundances in two NWA 2999 clinopyroxene grains (cpx A and B; B-1 and B-2 are analyses on two different spots near the core and rim, respectively, of grain B) (colored symbols). The ranges of REE abundances [10] in clinopyroxenes of the plutonic angrite LEW 86010 (black circles) and the quenched angrite Sahara 99555 (black squares) are also shown.

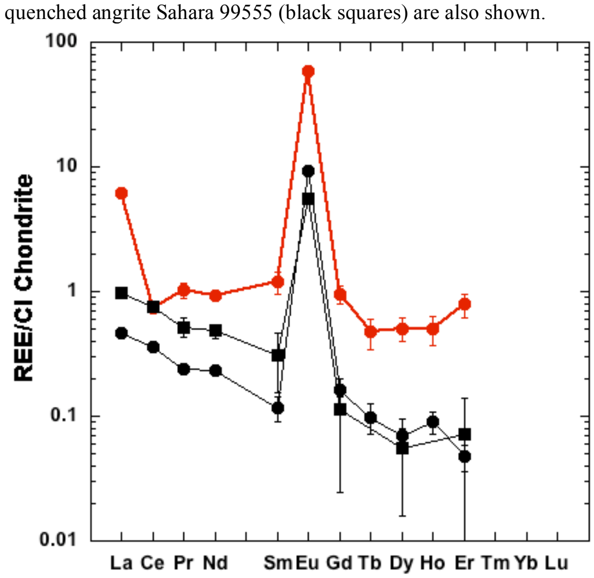

Figure 2. Representative REE abundances in anorthite of NWA 2999 (red symbols). For comparison, REE abundances [10] in anorthites of LEW 86010 (black circles) and Sahara 99555 (black squares) are also shown.

Anorthite in NWA 2999 has a LREE-enriched pattern with a large positive Eu anomaly (Eu/Eu*~50). Although the REE pattern is similar to that of anorthites in the other angrites, the REE concentrations are higher (5-10×) in the NWA 2999 anorthite (Fig. 2), and it also appears to exhibit a negative Ce anomaly (Ce/Ce*~0.2). Since NWA 2999 is a hot desert find, it is likely that this feature is due to terrestrial alteration [9]. Olivine in NWA 2999 exhibits a shallow V-shaped pattern, with the LREE-enrichment most likely resulting from terrestrial contamination due to weathering in a hot desert environment [9]. Nevertheless, the HREE pattern of this mineral (CI-normalized Lu/Gd ~30) is similar to that olivines in the other angrites (Fig. 3).

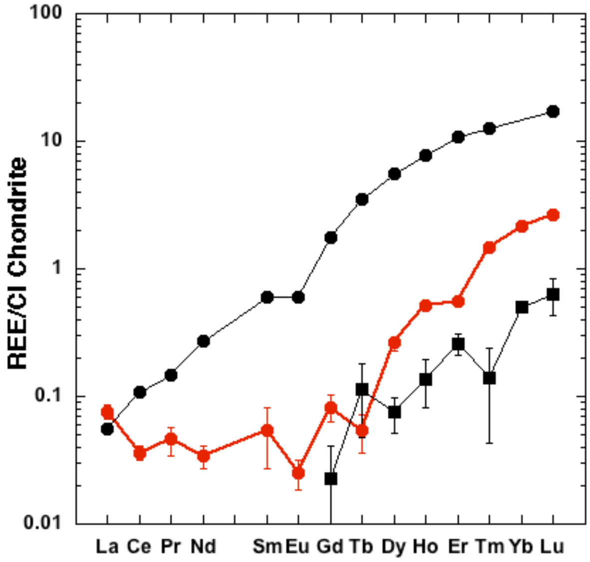

Figure 3. Representative REE abundances in olivine of NWA 2999 (red symbols). REE abundances [10] in olivines of LEW 86010 (black circles) and Sahara 99555 (black squares) are also shown.

To assess whether we sampled all the mineral phases that contribute to the REE inventory, we compared whole rock REE abundances reported for NWA 2999 by [6] with those calculated based on the REE abundances reported here combined with the modal abundances reported by [6]. Even allowing for the possibility of substantial variation in the modal abundance of clinopyroxene (the most REE-rich phase analyzed by us), the calculated REE pattern for the whole rock remains LREE-depleted compared to the actual whole rock REE pattern (Fig. 4). A trace amount (~0.04%) of a LREE-enriched phase such as merrillite (also reported in other angrites [10,11]) is required to account for the actual whole rock REE pattern; the fit is somewhat better with a phosphate REE composition similar to that of Sahara 99555 (red circles in Fig. 4) rather than of LEW 86010 (blue circles in Fig. 4). We also estimated the REE composition of the NWA 2999 parent melt by inverting the clinopyroxene core composition (Cpx B-1 in Fig. 1) using REE partition coefficients (D_{REE}) given in [10]. REE abundances calculated for the NWA 2999 parent melt agree with those estimated previously for other angrites (within a factor of ~2-3, which is not unreasonable given uncertainties in the absolute values of the D_{REE}), although the REE pattern of the NWA 2999 parent melt is most similar to that of Sahara 99555 (Fig. 4).

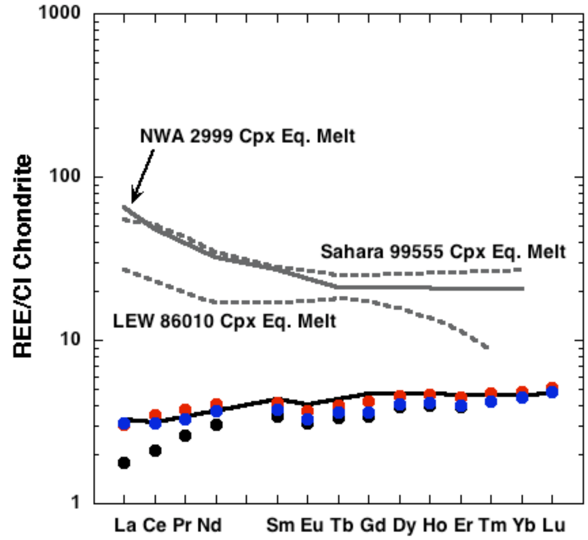

Figure 4. Results of mass balance calculations of whole rock abundances assuming ~64% olivine, ~30% clinopyroxene, ~1% anorthite, and ~15% phases having negligible REE abundances (black circles). Red and blue circles: same modal abundances as above but with the addition of ~0.04% phosphate with REE concentrations similar to those of Sahara 99555 [10] and LEW 86010 [11], respectively; solid black line: whole rock REE abundances reported by [6]; solid gray line: NWA 2999 parent melt calculated to be in equilibrium with its clinopyroxene core; dashed gray lines: melts calculated to be in equilibrium with clinopyroxene cores of Sahara 99555 and LEW 86010 [10,11].

In conclusion, REE microdistributions in NWA 2999 indicate that there are similarities as well as some differences between it and the other angrites. In particular, even though NWA 2999 is texturally similar to the plutonic angrites, its REE distributions appear to show distinct similarities to those in the Sahara 99555 quenched angrite. Therefore, this angrite may represent a petrogenetic link (particularly in terms of the REE composition of its parent magma) between the plutonic and the quenched angrites, although further analyses are required to confirm this.

References: [1] Mittlefehldt D. et al. (1998) *Rev. Mineralogy 36, Planetary Materials,* Chapter 4, pp. 195. [2] Amelin Y. (2007) *GCA, 72,* 221-232. [3] Connelly J. et al. (2007) *GCA,* in press. [4] Irving A. J. et al. (2005) *AGU,* Abstract #P51A-0898. [5] Kuehner S. M. et al. (2006) *LPS XXXVII*, Abstract #1344. [6] Gellissen M. et al. (2007) *LPS XXXVIII,* Abstract #1612. [7] Amelin Y. and Irving A. J. (2007) *Workshop on Chronology of Meteorites,* Abstract #4061. [8] Zinner E. and Crozaz G. (1986) *International Journal of Mass Spectrometry and Ion Processes, 69,* 17-38. [9] Crozaz G. et al. (2003) *GCA, 67,* 4727-4741. [10] Floss C. et al. (2003) *GCA, 67,* 4775-4789. [11] McKay G. et al. (1994) *GCA, 58,* 2911-2919.