MINERALOGICAL AND TRACE-ELEMENT CONSTRAINTS ON THE PETROGENSIS OF ANGRITES

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Introduction: Angrites are a relatively small group of meteorites (17 recognized stones with a combined mass of ~28 kg), with oxygen isotope compositions distinct from samples of the Earth, Moon, Mars and the howardite-eucrite-diogenite (HED) meteorite group [1]. Current Pb-Pb isotope chronology (with limited determinations of $^{238}U/^{235}U$ values) of angrites indicates that these meteorites are some of the most ancient crystalline rocks of the Solar System, and these materials provide a pivotal reference point for relative chronometry using short-lived radionuclides [e.g., 2-6]. Initial $^{87}Sr/^{86}Sr$ values of angrites are below the basaltic achondritic initial (BABI), which has been linked to volatile loss within ~ 2 Myr of CAI formation [7-10].

In general, angrites are regarded as igneous rocks, and contrast to other planetary magma products by exhibiting suprachondritic Ca/Al values and silica-undersaturated compositions [11-12]. Texturally, angrites fall in two groups; 1) quenched-angrites with a weighted mean age of 4562.1 ± 0.4 Ma; and 2) slowly-cooled angrites with a weighted mean age of 4557.7 ± 0.2 Ma [2-6]. All angrites are composed of an unusual assemblage dominated by anorthite, fassaitic pyroxene, and Ca-bearing olivine [11-12,14-17].

We present new major- and trace-element compositions of minerals in a suite of angrites (Angra dos Reis, D'Orbigny, Sahara 99555, NWA 4590, NWA 4801, and NWA 4931), in which we have also determined highly-siderophile-element abundances and osmium isotope compositions [13].

Petrography and Mineralogy of Angrites: Quenched-angrites (D'Orbigny and Sahara 99555) contain fassaitic pyroxene (up to 750 μm at the long-axis) and Ca-bearing olivine (up to 700 μm in maximum dimension) that exhibit pronounced major-element zonation (Fig. 1 and 2). Ca-bearing olivine is present in most of the crystallization sequence, and late-stage phases include kirschsteinite, ulvöspinel (20-80 μm), troilite (<50 μm), and silico-phosphates (<20 μm).

Slowly-cooled angrites are relatively coarse-grained (crystals are generally 0.5 to 2 mm at the long-axis; Fig. 1), and lack the pronounced compositional-zoning observed in quenched-angrites (Fig. 2). However, slowly-cooled angrites are texturally diverse. For example, NWA 4590 displays kirschsteinite and olivine exsolution features that are absent from NWA 4801. In addition, NWA 4590 contains rhönite [18] that is not observed in NWA 4801.

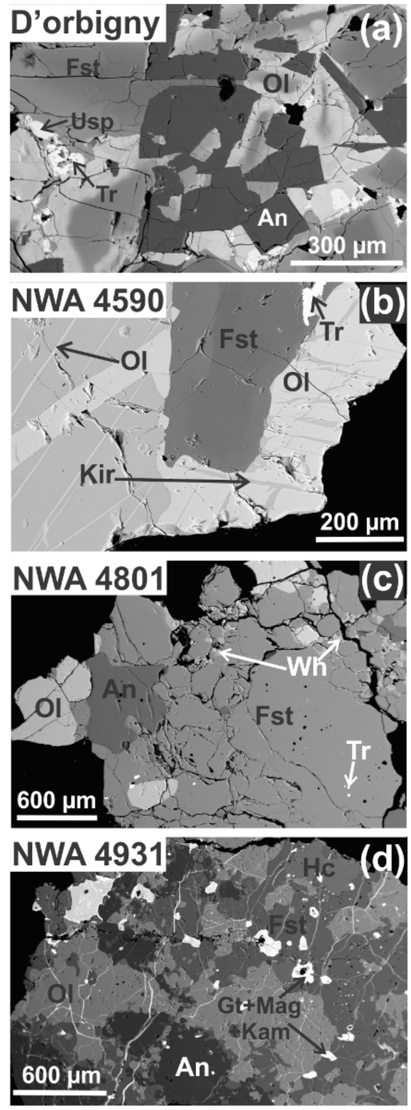

Figure 1: *Back-scattered electron (BSE) images of four angrites illustrating the textural diversity of this meteorite group. An = anorthite, Fst = fassaite, Gt = goethite, Hc = hercynite, Kam = kamacite, Kir = kirschsteinite, Mag = magnetite, Ol = olivine, Tr = troilite, Usp = ulvöspinel, Wh = whitlockite. (Note differences in scale for each image).*

NWA 4931 is a text urally distinct angrite containing anhedral silicates and hercynitic spinel (Fig. 1) of relatively uniform composition. NWA 4931 is textura-

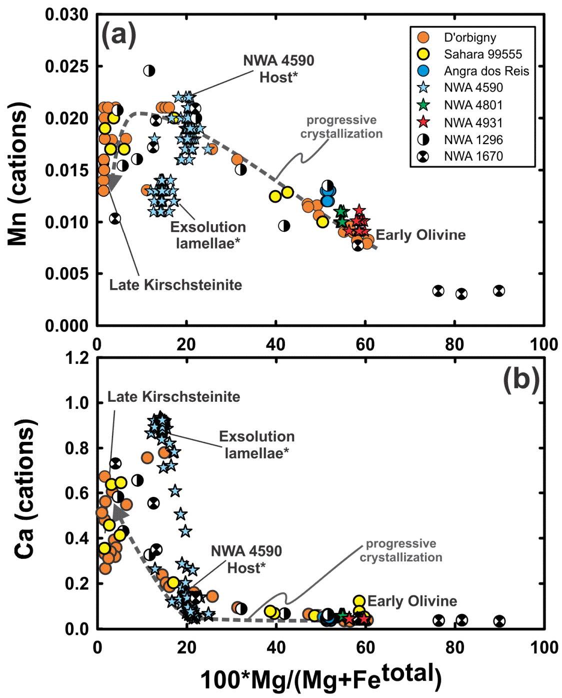

Figure 2: *Major-element compositions of constituent olivines of angrites. Cation values were calculated on the basis of four oxygens. Olivines of NWA 1296 and NWA 1670 were reported by [16-17].*Different olivine crystals of NWA 4590 contain inverted host and lamellae compositions.*

lly paired with NWA 2999, and both of these meteorites contain abundant kamacite [20] that is variably oxidized (magnetite) and hydrated (goethite); together this phase association accounts for ~6 vol. % of the bulk-sample.

The type-specimen of angrite, Angra dos Reis, is atypical when compared to all other angrites [e.g., 11]. Angra dos Reis is dominated by fassaitic pyroxene (91 to 93 vol. %) of relatively homogeneous major-element composition, whereas other angrites contain significantly more olivine and feldspar.

Trace-Element Compositions of Angrite Minerals: Constituent minerals of quenched- and slowly-cooled angrites display several characteristic features; 1) anorthite has a large positive Eu-anomaly; 2) pyroxene has a negative Eu-anomaly and light-rare-earth-element (LREE)-depleted profile; 3) phosphate has a negative Eu-anomaly and LREE-enriched profile; and 4) olivines are LREE-depleted and the abundance of REEs increases with increasing Ca-content. The presence of negative Eu-anomalies in pyroxene and phosphate may suggest that these minerals crystallized from a magma with a negative Eu-anomaly, and such a melt may develop when feldspar is an early crystallizing phase. Textural characteristics of D'Orbigny and Sahara 99555 are consistent with the notion that feldspar crystallized early in these magma products (Fig. 1a).

Discussion: The textural, major-, and trace-element characteristics of constituent minerals of the studied suite of angrites are similar to those reported in previous investigations [11-12,14-17]. Major- and trace-element systematics of pyroxenes and olivines may suggest that angrites are derived from magmas that have distinct crystallization histories and/or parent magmas (e.g., Fig. 2, [15]).

Quenched-angrites D'Orbigny and Sahara 99555 define similar fractionation trends and may be genetically related. These quenched-angrites may have a magmatic history similar to that of NWA 1296 [16]. Other quenched angrites, LEW 87051 and Asuka 881371, contain variable proportions of magnesian-olivine that is not in equilibrium with the groundmass, and these olivines may be xenocrystic [21]. It has been suggested that magmas parental to LEW 87051 and Asuka 881371 may be similar to those that crystallized D'Orbigny, Sahara 99555, and NWA 1296 [15,19,21].

Major- and trace-element systematics of constituent minerals of slowly-cooled angrites, NWA 4590 and NWA 4801, suggest that these broadly coeval magmas may have distinct crystallization histories or may be derived from melts distinct from one another and different to those that crystallized quenched-angrites [20]. In addition, Angra dos Reis may be derived from a separate magma batch, whereas NWA 4931 may contain a significant amount of impact material. These interpretations are similar to those reported in previous mineralogical and trace-element studies of angrites [11-12,15-17,19,21].

References: [1] Greenwood et al., 2005, Nature, 435, 916-918. [2] Connelly et al., 2008, GCA 72, 4813-4824. [3] Shukolykov and Lugmair, 2008, 39th LPSC, abstract# 2094. [4] Amelin et al., 2009, GCA 73, 5212-5223. [5] Nyquist et al., 2009, GCA 73, 5115-5136. [6] Brennecka et al., 2010, 41st LPSC, abstract# 2117. [7] Wasserburg et al., 1977, EPSL, 35, 294-316. [8] Lugmair and Galer, 1992, GCA, 56, 1673-1694. [9] Tonui et al., 2003, 34th LPSC, abstract# 1812. [10] Hans et al., 2010, 41st LPSC, abstract# 2680. [11] Mittlefehldt and Lindstrom., 1990, GCA, 54, 3209-3218. [12] Mittlefehldt et al., 1998, in Planet. Mat., Chpt. 4. [13] Riches et al., 2011, 42nd LPSC, this volume. [14] Mikouchi et al., 2000, 31st LPSC, abstract# 1970. [15] Floss et al., 2003, 67, 4775-4789. [16] Jambon et al., 2005, MAPS, 40, 361-375. [17] Jambon et al., 2008, MAPS, 43, 1783-1795. [18] Kuehner and Irving, 2007, 40th AGU, abstract# P41A-0219. [19] Prinz et al., 1990, Proc. of the 21st LPSC, p979. [20] Humayun et al., 2007, 38th LPSC, abstract# 1221. [21] Mikouchi et al., 2004, 35th LPSC, abstract# 1504. [22] Sanborn and Wadhwa, 2009, 40th LPSC, abstract# 1345.