

PETROGENESIS OF THE DIFFERENTIATED ACHONDRITE GRA 06129: TRACE ELEMENTS AND CHRONOLOGY R.D. Ash¹, J.M.D. Day¹, W.F. McDonough¹, J. Bellucci¹, D. Rumble III², Y. Liu³ and L.A. Taylor³ ¹Dept. Geology, Univ. Maryland, College Park, MD 20740 (rdash@geol.umd.edu, jamesday@geol.umd.edu); ²Dept. Geophysical Lab, Carnegie Institution, Washington DC 20015; ³Planetary Science Institute, Dept. Earth Planet. Sci., Univ. Tennessee, Knoxville, TN, 37996.

Introduction: Initial descriptions of GRA 06129 and GRA 06128 show that they are curious, anomalous achondrites consisting largely of sodic plagioclase. Oxygen isotope analysis (mean $\Delta^{17}\text{O} = -0.06\text{‰}$) [1] has added to the enigmatic nature of the meteorite lying close to the angrite fractionation line ($\Delta^{17}\text{O} = -0.07\text{‰}$) [2]. However there is little supporting evidence from mineralogy for an affiliation with the angrite clan. The proximity of the oxygen isotopic composition to the TFL cannot exclude a relationship with the Earth-Moon system, or with the enstatite chondrites/aubrites. However, again, there is nothing in the mineralogy to suggest any relationship.

GRA 06129 is a partially fusion crusted, weathered stone, with medium- to coarse-grained phaneritic texture. It is composed of oligoclase (modal percentage 75%), fayalitic olivine (10%), subequal amounts of orthopyroxene and augite (10%), sulphide, co-existing troilite and pentlandite (2.6%) and phosphate minerals - chlorapatite (1.9%) and merrillite (0.7%) - with minor quantities of ilmenite and Cr-spinel [3].

Herein are the results of a laser-ablation ICP-MS study aimed at constraining the petrogenesis, origins and relations of GRA 06129.

Methods: Electron microprobe (EMP) analyses of a thick polished section of GRA 06129 were performed at the University of Tennessee [3]. Mineralogically characterised minerals were subsequently ablated using a New Wave Research UP213 laser coupled to a ThermoFinnigan Element 2 ICP-MS at the University of Maryland, following methods outlined in [4].

Olivine, pyroxene, plagioclase, phosphate and sulphide were analysed using a spot-size ranging from 15 to 80 μm for minor and trace elements as well as the rare earth elements (REE). Th/ThO production was *ca* 0.07%. The four Pb isotopes were measured concurrently to provide preliminary age constraints.

Results: GRA 06129 has a very restricted range in silicate mineral major and trace element compositions. Augites have depleted LREE patterns, and orthopyroxenes have measurable quantities of only the HREE. Oligoclase is characterised by low concentrations of REE. LREE and Eu can be measured and, with the limited HREE data, demonstrate a positive Eu anomaly and a slight enrichment in LREE. Despite making up only 2.5% of the sample the phosphates are the major carriers of REE, with merrillite containing 110-

250xCI. Both merrillite and chlorapatite show slight LREE enrichments, but merrillite has a negative, and chlorapatite a positive, Eu anomaly (Fig. 1). The concentrations are lower than typically observed in lunar phosphates and the relative concentrations in merrillite and chlorapatite reversed [*e.g.*5]. The presence of a positive Eu anomaly in chlorapatite is unusual, but not unknown in terrestrial materials.

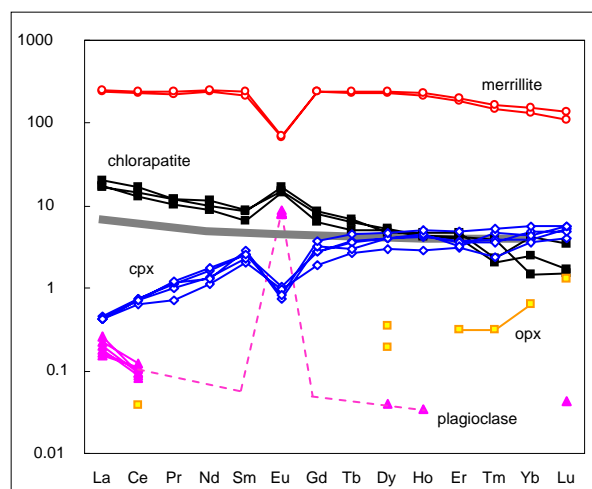


Figure 1: CI normalized rare earth element profiles for augite, orthopyroxene, plagioclase and phosphates in GRA 06129. Grey line shows calculated initial REE of the parent melt.

Concentration ranges in incompatible elements within plagioclase (70 \pm 2ppm Sr, 470 \pm 43ppm Ti, 93 \pm 4ppm Ga and 36.9 \pm 1.4ppm Ba) and pyroxenes are limited, with clinopyroxene being consistently enriched in Cr (3372 \pm 508ppm), V (798 \pm 63ppm) and incompatible elements relative to orthopyroxene (Cr = 489 \pm 15ppm; V = 121 \pm 35ppm). A striking feature of the cpx data is the consistently high abundance of Sc (205 \pm 9ppm) relative to opx (30 \pm 7ppm).

Olivines are also compositionally homogeneous (Fo_{39.6 \pm 0.2}; 558 \pm 200ppm Ni; 240 \pm 6ppm Co; 30 \pm 10ppm Cr; 51 \pm 6ppm Ti) and have low CaO (<0.11wt%). Two types of sulphide co-exist in GRA 06129, troilite and pentlandite. Both have measurable quantities of the chalcophile and platinum group elements, in some cases ppm quantities.

Discussion: GRA 06129 has a phaneritic or granoblastic texture and variable grain-size, with evidence for pyroxene exsolution, sulphide segregation

and extreme homogeneity in mineral compositions: there is no clear evidence for incompatible element crystallization trends within minerals. GRA 06129 has features that suggest a sub-solidus re-equilibration or thermal metamorphic event in its history. It can also be considered to be monolithological based on compositional homogeneity. Two-pyroxene thermometry yields a range of possible temperatures, up to $\sim 845^\circ\text{C}$ for any re-equilibration event [3]. Sulphides in GRA 06129 contain measurable quantities of highly siderophile elements which may indicate impact-related origin.

Despite the weathered nature of GRA 06129, with evidence for alteration in cracks and around sulphides, we cannot distinguish the presence of Ce-anomalies in the cores of minerals that were ablated. Positive Eu-anomalies in the plagioclase ($\text{Eu}/\text{Eu}^* \sim 200$) and complementary negative anomalies in the augite ($\text{Eu}/\text{Eu}^* \sim 0.23\text{--}0.46$) indicate a low $\text{Eu}^{3+}/\text{Eu}^{2+}$ ratio and low $f\text{O}_2$ during formation of GRA 06129.

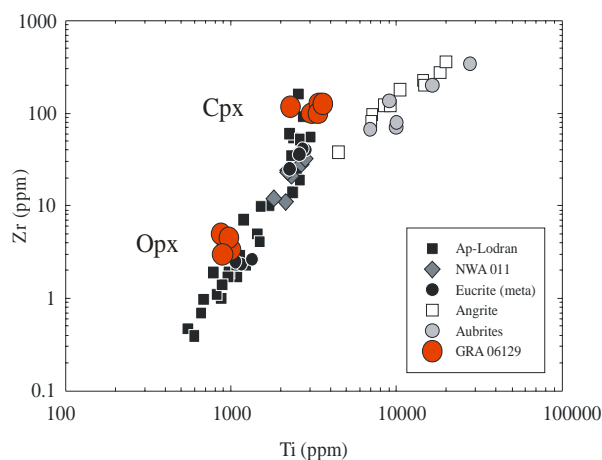


Figure 2: Ti versus Zr in pyroxenes for differentiated achondritic meteorites.

Re-equilibration is a common occurrence on differentiated achondrites [6]. Fig. 2 shows a plot of Ti versus Zr for silicate achondrites. GRA 06129 pyroxenes plot with those from Acapulcoite-Lodranites, metamorphosed eucrites and NWA 011, although O-isotopes preclude a genetic link with any of these meteorite types. Pyroxenes in the aubrites and angrites, which possess the closest O-isotope compositions to GRA, are systematically higher in Ti, although aubrites are the only differentiated achondrites with comparably high-Sc pyroxenes to GRA 06129. If silicates in GRA 06129 have preserved original igneous signatures or REE compositions of their parental melts can be calculated. Distribution coefficients which broadly approximate the compositions of minerals in GRA 06129 were used to calculate liquids in equilib-

rium with plagioclase and pyroxene grains [7, 8] and indicate a slightly light REE-enriched (LREE = $\sim 8 \times \text{CI}$, HREE = $3 \times \text{CI}$) parental melt composition [Fig. 1].

Chronology: As a by-product of trace element analysis of phosphates the high levels of U (*ca.* 500ppb) in chlorapatites enabled ^{206}Pb - ^{207}Pb ages to be determined on the three grains, merrillite contained insufficient U (<60ppb) for meaningful ages to be measured. Despite relatively large errors these preliminary measurements show the rock to be old, *ca.* 4.55Ga. We expect to improve precision with dedicated age measurement.

	[U]ppm	Th [ppm]	Age (Ma)	1 σ
Cl-apatite	0.44	1.1	4570	300
Merrillite	<0.06	1.0		
Cl-apatite	0.58	1.3	4640	120
Cl-apatite	0.52	1.3	4410	110
Merrillite	0.02	0.8		

Table 1. ^{206}Pb - ^{207}Pb ages for 5 phosphate grains in GRA 06129

Although the U content of the merrillites prevented dating during the initial analysis, they exhibit a hundred fold enrichment in Lu over chondritic, and an order of magnitude depletion in Zr over CI, suggesting that the merrillites are excellent candidates for Lu-Hf dating.

These ages are difficult to reconcile with an origin in the Earth-Moon system.

Conclusions: GRA 06129 appears to represent early formed lower crustal material from a differentiated Na-plagioclase-rich planetesimal but, thus far, the combination of petrology, geochemistry and O-isotopes appear to preclude grouping with any known meteorite groups, lunar or terrestrial samples. Continued detailed isotopic and elemental studies of GRA 06129 may reveal information on early crustal processes and differentiation mechanisms for solar-system bodies.

References: [1] Antarctic Meteorite Newsletter (2007), **30** (2). [2] Greenwood *et al.*, (2005) *Nature* **435**, 916-918. [3] Liu Y. *et al.* (2008) *LPSC XXXIX*, this volume. [4] Brenan J.M. *et al.* (2005) *EPSL*, **237**, 855-872. [5] Anand *et al.*, (2003) *Geochim. Cosmochim. Acta* **67**, 3499-3518. [6] Mittlefehldt D.W. (2003) *Treatise on Geochemistry*, **Vol 1**, 291-324. [7] Jones J.H. (1995) *In: Rock physics and phase relations, a handbook of physical constants*, pp. 73-104. [8] McKay G. *et al.* (1986) *Geochim. Cosmochim. Acta*. **50**, 920-937.