

**Petrology, Geochemistry, and Likely Provenance of Unique Achondrite Graves Nunataks 06128.** R. A. Zeigler<sup>1</sup>, B. L. Jolliff<sup>1</sup>, R. L. Korotev<sup>1</sup>, D. Rumble, III<sup>2</sup>, P. K. Carpenter<sup>1</sup>, and A. Wang<sup>1</sup>. Dept. Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, Campus Box 1169, Saint Louis, MO, 63130 (zeigler@levee.wustl.edu), <sup>2</sup>Geophysical Laboratory, Carnegie Institution, Washington, DC 20015.

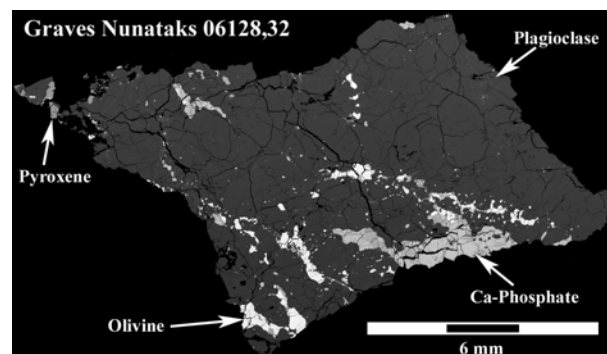
**Introduction:** Two “ungrouped” achondrite stones, Graves Nunataks (GRA) 06128 and 06129 (447.6 and 196.5 g) were collected during the 2006 ANSMET (the Antarctic search for meteorites) field season. The proximity of their find locations and initial petrographic descriptions [1] strongly suggest that they are paired. We characterize the petrography and geochemistry of GRA 06128 and use this data, in concert with oxygen isotopic ratios, to assess whether GRA 06128 is related to any known group of achondrites.

**Methods:** Concentrations of some elements in bulk samples of GRA 06128 were determined by INAA (instrumental neutron activation analysis). Petrography was determined on a thin section and two thick sections (~1 cm<sup>2</sup> total area). Quantitative mineral compositions were determined by EPMA (electron-probe microanalysis) on a JEOL 8200 Superprobe. Laser Raman spot analyses were performed using a with Kaiser Hololab 3000 Raman spectrometer using a 532 nm laser. Oxygen isotopic ratios (Table 1) were determined by laser fluorination of two coarsely ground subsamples (~2 mg each). Crushed samples were soaked in dilute HCL and ultrasonicated to remove weathering products. Magnetic grains were removed with a permanent magnet.

**Petrography:** GRA 06128 is a coarse-grained troctolitic anorthosite with granoblastic texture dominated by plagioclase (~90% by mode), with minor amounts of Ca-phosphate (~5%), olivine (~4%), and pyroxene (<1%), and trace amounts of oxides, sulfides, and metal (Fig. 1). Plagioclase grains are large (up to 5 mm) and equilibrated (Ab<sub>12-14.5</sub>Or<sub>1.7-2.1</sub>). Olivine grains (0.01-1.5 mm) are Fe-rich and equilibrated (Fo<sub>39.5±1</sub>), with low concentrations of CaO (0.09 wt%), Cr<sub>2</sub>O<sub>3</sub> (<0.03 wt%), and measurable amounts of NiO (0.05 wt%) and ZnO (0.03 wt%). Pyroxene typically occurs as small (<30 μm) equilibrated orthopyroxene (Wo<sub>2</sub>En<sub>52</sub>) and augite (Wo<sub>43</sub>En<sub>37.5</sub>) grains spatially associated with olivine. A few large augite grains (up to 0.8 mm) with narrow orthopyroxene lamellae (1-2 μm) are also present. Two types of Ca-phosphate are present in GRA 06128: chlorapatite and Na-merrillite. They occur intergrown in grains up to 5 mm long. The apatite has a Cl:F value of 0.78 and both phosphates have REE concentrations that are relatively low (i.e., <0.05 wt% Ce<sub>2</sub>O<sub>3</sub>). Chromite and ulvöspinel typically occur in GRA 06128 as small (<30 μm) grains. The chromite grains (34 wt% Cr<sub>2</sub>O<sub>3</sub>, 12.6 wt% TiO<sub>2</sub>, 4 wt% Al<sub>2</sub>O<sub>3</sub>) are usually found as inclusions within olivine, whereas ulvöspinel grains usually occur as inclusions within plagioclase. In some

cases, the ulvöspinel occurs as lamellae (<8 μm) within chromite grains. Both grains contain little MgO (<1.5 wt%) and the chromite grains contain high V<sub>2</sub>O<sub>3</sub> (2.7 wt%) and measurable ZnO (0.23 wt%). Troilite and pentlandite (up to 26 wt% Ni and 2.4 wt% Co) are found in GRA 06128, primarily as strings of tiny blebs (<10 μm in diameter) that occur mostly along relict or annealed grain boundaries. A few larger troilite grains (up to ~150 μm) are also found. FeNi metal (67 wt% Ni, 0.8 wt% Co) occurs intergrown in tiny blebs with pentlandite. Shock alteration in GRA 06128 is minor; however, the sample is moderately fractured and some undulatory extinction is seen in plagioclase. The sample is considerably altered, more so than other Antarctic meteorites. Preliminary laser Raman spot analyses reveal gypsum and possibly bassanite (CaSO<sub>4</sub>·½H<sub>2</sub>O) on exterior surfaces of the meteorite, whereas electron microprobe EDS analyses on the bright material filling fractures show suspected Fe sulfates and oxides, including an Fe,K sulfate, possibly jarosite. The fusion crust is relatively narrow (~50 μm) and vesicular.

**Geochemistry:** On the basis of preliminary INAA data, GRA 06128 has high concentrations of Na<sub>2</sub>O (6.3 wt%), but low concentrations of other alkali and alkali-earth elements (e.g., 27 ppm Ba). Concentrations of FeO are surprisingly high (13.6 wt%) given the plagioclase-rich nature of our section; neither Sc (4.5 ppm) or Cr (225 ppm) is present in high concentrations, however. (Even feldspathic lunar meteorites with only 3–7% FeO contain 8±4 ppm Sc and 700±300 ppm Cr.) Incompatible-trace element (ITE) concentrations are low (e.g., 0.34±0.17 ppm Sm, 0.07±0.03 ppm Th), typically <2x chondritic values [2]. The REE pattern (Fig. 2) is slightly light-REE enriched (La 2x, Yb 1.1x chondrite) with a positive Eu anomaly (5x). Siderophile element concentrations (2040 ppm Ni, 51 ppb Ir) are very high for an achondrite [3 and references therein] and ratios



**Figure 1:** Back-scattered electron mosaic image of GRA 06128.

such as Ni/Co (12.7), Ni/Ir (40,275), and Ir/Au (9.2) are not consistent with chondritic metal, but are consistent with some iron meteorite groups [3].

**Discussion:** On the basis of texture, mineral assemblage, and equilibrated mineral compositions, GRA 06128 appears to be a floatation cumulate. The bulk composition of GRA 06128 is relatively primitive, with low ITE concentrations (Fig. 2), suggesting that GRA 06128 formed early in its parent body's history from a parental magma of near chondritic composition. The initial description of GRA 06128 (on multiple thin sections) noted a wide range in grain sizes (from 5 mm to much less than 1 mm), suggesting the rock is a breccia [1]. The presence of high concentrations of siderophile elements and a vesicular fusion crust are further evidence that this rock originates from the upper meter or so of the parent body (to allow for implantation of the solar wind volatiles that likely caused the vesicular fusion crust).

But from which solar system body did GRA 06128 come? Oxygen isotopic measurements in this study ( $\Delta^{17}\text{O} = -0.21$ ; Table 1), which differ somewhat from those of [1], place GRA 06128 close to, but just below, the terrestrial fractionation line (TFL). This rules most of the various achondrite groups: martian meteorites ( $\Delta^{17}\text{O} = 0.27$ ), aubrites (0.03), winnonaites (-0.5), acapulcoites-lodranites (-1.04, -1.18), ureilites (-1.2), the IAB, IIE, and IVA silicate inclusions (-0.48, 0.59, 1.17), and lunar meteorites (on the TFL) [4,5, and references therein]. The Moon is a tempting parent body for GRA 06128 due to the abundance of anorthosite there. In addition to differences in oxygen isotopic ratios, several geochemical characteristics of GRA 06128 rule out the Moon, however: plagioclase is too sodic and lacks a corresponding ITE-enrichment, merrillite is Na-rich whereas lunar merrillite is REE-rich, and the Fe:Mn ratio, which has been shown to be diagnostic of meteorite parent bodies [6,7] is lower in GRA 06128 pyroxenes (40) and olivines (68) than in lunar pyroxene (~65) and olivine (~100). Angrites and HEDs have oxygen isotope ratios ( $\Delta^{17}\text{O} = -0.15 \pm 0.06$  and  $-0.25 \pm 0.08$  respectively) indistinguishable from GRA 06128. The parent bodies of these achondrite groups, however, are exceptionally depleted in volatile elements (especially Na), as evidenced by both the calcic nature of the plagioclase and the bulk composition [3]. Mesosiderites and pallasites also have oxygen isotope ratios indistinguishable from GRA 06128 ( $\Delta^{17}\text{O} = -0.24 \pm 0.09$  and  $-0.28 \pm 0.06$ ); the Fe:Mn ratios in pyroxene (~20) and olivine (~40) are significantly different, however [3].

Of the known achondrite groups, brachinites are by far the best match. The average oxygen isotope composition of the brachinite group ( $\Delta^{17}\text{O} = -0.26 \pm 0.08$  [5]) is indistinguishable from GRA 06128. The Fe:Mn ratios in brachinite pyroxene (30-40) and olivine (60-70) are also identical to GRA 06128 [3,8,9]. Brachinites contain oligoclase ( $\text{An}_{20-30}\text{Or}_{<2}$ ) of similar (but slightly more calcic) composition; olivine ( $\text{Fo}_{68}$ ), and pyroxene ( $\text{Wo}_2\text{En}_{72}$ ;  $\text{Wo}_{45}\text{En}_{45}$ ) are considerably more magnesian, however [3,9]. This is not surprising since we are comparing ultramafic mantle cumulates and crustal anorthosites. A similar compositional disparity is seen when comparing lunar picritic glasses and ferroan anorthosite, or diogenites and basaltic eucrites. Moreover, minor-element variations in brachinite and GRA 06128 olivines do match, e.g. NiO, CaO, and  $\text{Cr}_2\text{O}_3$  concentrations [10,11]. Accessory minerals found in brachinites are similar to those found in GRA 06128: chromite, chlorapatite, Na-merrillite, troilite, pentlandite, and Ni-rich (up to 55 wt%) metal [11,12]. The bulk compositions of ultramafic brachinites are difficult to compare to GRA 06128. The REE pattern (Fig. 2; [9]) of the most ultramafic brachinite (ALH 84025), thought to be a mantle cumulate (dunitic wehrlite [9]), is light-REE depleted, subchondritic, and looks complementary to GRA 06128, as would be expected if both were derivatives of a brachinite parent body molten zone. Although the data are still preliminary, GRA 06128 appears to be member of the brachinite achondrite group, representing a near-surface breccia of early crystallized floatation cumulate material.

**References:** [1] McCoy T. J. et al. (2007) *Ant. Met. News.*, 30, no. 2. [2] Anders E. and Grevesse N. (1989) *GCA.*, 53, 197-214. [3] Mittlefehldt D. W. (1998) *Planet. Mats. Chpt 4, in Rev. Mineral.36.* [4] Lodders K. and Fegley B., Jr (1998) *The Planet. Sci. Comp.*, p 330-331. [5] Clayton R. N. and Mayeda T. K. (1996) *GCA*, 60, 1999-2017. [6] Dymek R. F. et al. (1976) *GCA.*, 40, 1115-30. [7] Papike J. J. (1998) *Planet. Mats. Chpt 7, in Rev. Mineral.36.* [8] Nehru C. E. et al. (1982) *PLPSC 12*, A365-373. [9] Warren P. H. and Kallemeyn G. W. (1989) *PLPSC 19*, 475-86. [10] Goodrich C. A. and Righter K. (2000) *MAPS*, 35, 521-36. [11] Nehru C.E. et al., (1992) *MAPS*, 27, 267 (abstract). [12] Irving A.J. Pers. Commun.

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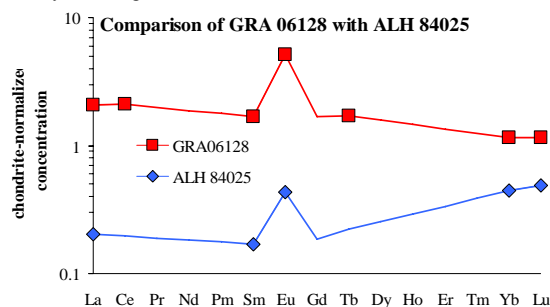


Fig. 2: Chondrite normalized REE diagram [2] comparing GRA 06128 and ALH 84025