

**GRA06129: A meteorite from a new asteroidal geochemical reservoir or Venus?** C.K. Shearer<sup>1</sup>, J.J. Papike<sup>1</sup>, P.V. Burger<sup>1</sup>, J. Karner<sup>1</sup>, L. Borg<sup>2</sup>, A. Gaffney<sup>2</sup>, C. Neal<sup>3</sup>, J. Shafer<sup>3</sup>, V.A. Fernandes<sup>4</sup>, Z. Sharp<sup>5</sup>, B.P. Weiss<sup>6</sup>, and J. Geissman<sup>5</sup>. <sup>1</sup>Institute of Meteoritics, Dept. of Earth and Planetary Sciences, Univ. of New Mexico, Albuquerque, NM 87131 ([cshearer@unm.edu](mailto:cshearer@unm.edu)); <sup>2</sup>Institute of Geophys. and Planetary Phys, Lawrence Livermore National Laboratory, Livermore, CA, 94550; <sup>3</sup>Dept. of Civil Eng. and Geology, Univ. of Notre Dame; <sup>4</sup>Berkeley Geochronology Center, Berkeley, CA 94709; <sup>5</sup>Dept. of Earth and Planetary Sciences, Univ. of NM, Albuquerque, NM 87131; <sup>6</sup>Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

**Introduction:** Achondritic meteorites commonly represent remnants of magmatic systems from differentiated planets (e.g. Moon, Mars) or asteroids (e.g. HED, acapulcoites, lodranites). They may represent products of early whole planetary melting such as the lunar ferroan anorthosites, remnants of low degrees of melting such as the acapulcoites and lodranites, or episodes of mantle melting such as the mare basalts and shergottites. Newly discovered achondritic meteorites GRA06128 and 06129 do not appear to fit within the planetary or petrologic context of any of these other achondrites. Preliminary oxygen isotopic compositions of these two meteorites lie along the terrestrial fractionation line. The initial description of a lithology with high content of sodic plagioclase and fairly Fe-rich silicates implied a fairly “evolved” planetary lithology compared to HED, lunar, and martian basaltic lithologies. Here, we summarize the preliminary findings of our consortium that has applied a wide range of analytical techniques to help decipher the petrogenesis and origin of this unusual meteorite.

**Analytical approach:** One thin section of GRA 06129 (23) and a sample mass of approximately 6 grams were analyzed in this study. Olivine, pyroxene, plagioclase, phosphates, metal, and oxides in this sample were first imaged and mapped by SEM followed by major element analysis using a JEOL JXA-8200 electron microprobe. Select phases were analyzed for a suite of trace elements using a Cameca 4f ims ion microprobe (University of New Mexico, UNM). Major, minor, and trace element analyses were obtained by ICP-MS at the University of Notre Dame. Analysis of O, S, and Cl stable isotopes were performed at the UNM. Magnetic properties were measured at MIT and UNM. Ar-Ar measurements will be conducted by the Berkeley Geochronology Center. The Sm-Nd and Rb-Sr chemistry was performed at LLNL, while the analyses were made at U.C. Berkeley.

#### Results:

**Modal mineralogy, textures, and distribution of phases:** GRA06129,23 exhibits a heterogeneous, granoblastic texture (Figure 1) with a modal mineral-

ogy dominated by fairly sodic plagioclase ( $\approx 81\%$ ). Two pyroxenes (orthopyroxene and Ca-rich clinopyroxene) and olivine are the most common silicates after plagioclase making up approximately 9% and 8%, respectively. Olivine contains inclusions of Fe-Ni metal, troilite, and pentlandite. Apatite overgrowths on merrillite occur in masses of up to 600  $\mu\text{m}$ . The modal abundance of phosphates is approximately 0.5%. Trace abundances of ilmenite and “spinel” are distributed throughout the section. Substantial Fe-rich alteration occurs along mineral surfaces (not included in mode).

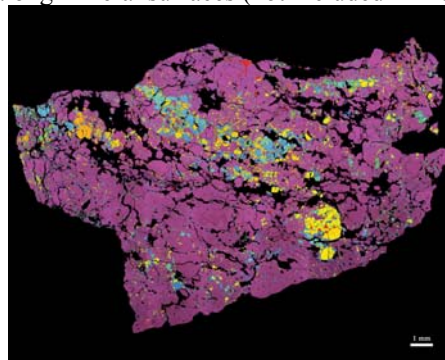


Figure 1. False color BSE composite image of thin section GRA06129, 23. Purple=plagioclase, blue=orthopyroxene and clinopyroxene, orange-yellow=olivine, blue green =phosphates, red=Fe-bearing oxides, sulfides and metals.

**Bulk Rock Composition:** The bulk rock is high in  $\text{Al}_2\text{O}_3$  (15.5 wt.%),  $\text{CaO}$  (6.22 wt. %), and  $\text{Na}_2\text{O}$  (7.51 wt.%). The  $\text{CaO}/\text{Al}_2\text{O}_3$  is 0.40, while the  $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{K}_2\text{O})$  (wt.%) is 0.033. The  $\text{MnO}/\text{FeO}$  is 0.0086 (assuming total Fe as FeO). The high phosphate modal abundance is evident in the overall  $\text{P}_2\text{O}_5$  of the bulk rock (0.19%). Although the high Na content and abundant phosphates imply an “evolved rock”, the overall trace element characteristics do not support this inference. The REE pattern is fairly flat (1 to 2 x chondrite) with a positive Eu anomaly (5 x chondrite). Ni and Co are 2215 ppm and 297 ppm, respectively. The bulk Rb/Sr is 0.028.

**Mineral compositions:** The composition of olivine is fairly restricted (Figure 3) with regards to Mg#

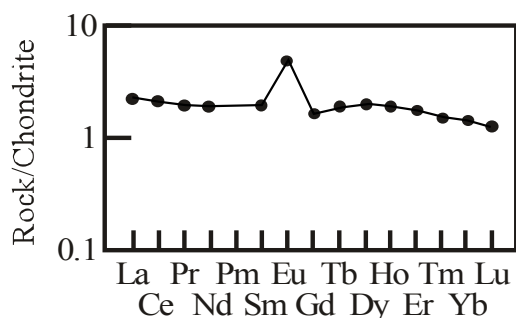


Figure 2. REE pattern of GRA06129 (mass 1 gram).

( $\text{Fo}_{41-40}$ ) and  $\text{Cr}_2\text{O}_3$  (0.00-0.07 wt.%).  $\text{CaO}$  (0.01-0.17 wt.%) is variable. One olivine grain adjacent to a spinel has a slightly higher Mg# ( $\text{Fo}_{45-42}$ ) and  $\text{Cr}_2\text{O}_3$  (0.02-0.31 wt.%). The high-Ca pyroxene ranges in composition from  $\text{En}_{39}\text{Fs}_{16}\text{Wo}_{45}$  to  $\text{En}_{44}\text{Fs}_{29}\text{Wo}_{27}$  (Figure 3). Most grains exhibit exsolution of low-Ca pyroxene on the scale of  $2\mu\text{m}$  or less. Exsolution on this scale results in the extension of the pyroxene compositions to lower Wo (Figure 3). The compositional variation in orthopyroxene is limited with an average composition of  $\text{En}_{53}\text{Fs}_{45}\text{Wo}_2$  (Figure 3). There is approximately 2-3% “others” components (Na,  $\text{Fe}^{3+}$ ,  $\text{Al}^{\text{VI}}$ , Ti, Mn) in the M1-M2 site of the high-Ca pyroxene, whereas these components makeup only 1% of the M1-M2 site in orthopyroxene. Based on the stoichiometry of approximately 100 microprobe analyses, the average ferric iron ( $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ ) in the high-Ca pyroxene is 7%. As expected, the orthopyroxene has less ferric iron (commonly less than 1% total iron), while the iron in olivine is essentially all ferrous. Much like the other silicates, plagioclase exhibits a very limited range in composition, from  $\text{An}_{16}\text{Ab}_{82}\text{Or}_2$  to  $\text{An}_{13}\text{Ab}_{85}\text{Or}_2$  ( $n=141$ ). Apatite is halogen-rich ( $\text{Cl}\approx 5.0\%$ ,  $\text{F}\approx 0.7\%$ ), whereas the merrillite is halogen-poor with substantial Na in the CaIIA site ( $\approx 2.5\%$ ). A significant number of phases make up the metal, oxide, and sulfide assemblage. The ilmenite composition does not contain a hematite component, although there is approximately 7%  $\text{MgTiO}_3$ . The “spinel” composition is dominated by a chromite component with minor spinel and ulvöspinel components. Spinel stoichiometry suggests minor amounts of ferric iron ( $(\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})) = 3\%$ ).

**Trace Element Composition of Mineral Phases :** The Ni and Co abundance of the olivine is fairly low and suggest that the Ni and Co is partitioned into the associated Ni-bearing metals and sulfides. The REE abundances of the phosphates are both relatively low with the merrillite ( $\text{Ce}\approx 125\times\text{CI}$ ) $\gg$ apatite ( $\text{Ce}\approx 10\times\text{CI}$ ).

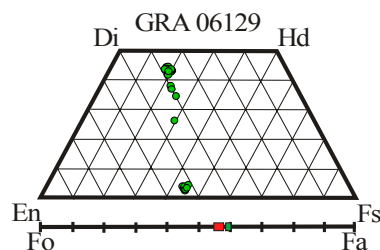


Figure 3. Compositions of olivine and pyroxene from GRA 06129,23. Olivine composition represented by red field is a single olivine in direct contact with spinel.

### Discussion:

**Conditions of formation:** Because of the fairly low “others” component in the pyroxene, the pyroxene thermometry of [1] may be used to approximate the temperature under which the pyroxene pairs last equilibrated. Using this thermometer the temperature of pyroxene equilibration is approximately  $670\pm 50^\circ\text{C}$ . Other phases such as spinel-olivine record a slightly higher temperature ( $\approx 900\pm 50^\circ\text{C}$ ). The ferric iron content of pyroxene in GRA06129 implies an  $f_{\text{O}_2}$  more oxidizing than the Moon (IW-1) as lunar pyroxenes contain no ferric iron. Preliminary estimates of  $f_{\text{O}_2}$  suggest conditions more oxidizing than IW+2.

**Planetary body of origin:** Although initial oxygen isotopic compositions are consistent with an origin in the Earth-Moon system, numerous observations appear to eliminate both bodies. For example, estimates of  $f_{\text{O}_2}$  seems to eliminate Earth while high-Na content (in the bulk rock and mineral phases) seems to eliminate the Moon. Further, the Mn/Fe ratio of olivine and pyroxene does not fit either planetary body, although the comparison between GRA06129 and terrestrial-lunar basalts is perhaps not entirely restrictive.

Venus has been discussed as a possible source for this meteorite. However, there are numerous unknowns concerning the lithologies making up the venusian crust. Geochemical data from Venera 13, 14 and Vega 2 [2] indicate a crust dominated by basalts and not lithologies represented by GRA06129, although recent modeling indicates a diversity of rocks on Venus [3].

Small degrees of early melting and efficient melt extraction on a small planetary body could produce a lithology similar to GRA06129. Chondrite melting experiments of [4] produced high Na melts with REE patterns similar to GRA06129. These small melt fractions could be analogous to melts removed from lodranites. However, the oxygen composition and the Fe/Mn ratio of the silicates indicate that this lithology is not from the acapulcoites-lodranite parent body.

**References:** [1] Lindsley (1983) *Am. Mineral.* 68, 477-493. [2] Surkov (1984) *LPSC 14<sup>th</sup>*, B393-B. [3] Elkins-Tanton et al. (2007) *JGR* 112. [4] Feldstein et al. (2001) *MAPS* 36, 1421-1441.