SEARCHING FOR THE EVOLVED CRUST OF OXIDIZED ASTEROIDS.

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Introduction: The recently discovered paired achondrite meteorites Graves Nunatak (GRA) 06128 and 06129 are an ancient lithology (4.52 ± 0.06Ga metamorphic age) thought to be the previously unsampled crust of an evolved asteroid [1, 2]. GRA 06128/9 are unique in many ways including their elevated sodic plagioclase (PLG) abundance and remarkably FeO-rich mafic silicates (**Table 1**). GRA 06128/9 are more enriched in FeO than previously observed igneous meteorites, which points to the melting of an oxidized precursor. These high PLG abundance is reminiscent of lunar ferroan anorthosites. However rather than formation from PLG segregation in a asteroidal magma ocean, GRA 06128/9 are now thought to be samples of a crust formed through ~10 to 30% partial melting of volatile-rich, oxidized asteroid [1].

There is now mounting geochemical and petrological evidence for a relationship between GRA 06128/9 and the brachinites [2, 3]. Like GRA 069128/9, brachinites are FeO-rich (~Fo_{60}) and contain similar trace mineral phases, oxygen isotope compositions, and fractionated highly siderophile element patterns [2]. Thus, the brachinites may represent the olivine-rich (OLV) residue predicted to compliment the GRA 06128/9 partial melt [1]. However, the exact circumstances of GRA 06128/9's formation remain uncertain.

Table 1: Average GRA 06128/9 Mineralogy

Mineral	Abundance	Composition
PLG (oligoclase)	75%	Ab_{84} (Na-rich)
OLV	9%	Fo_{40}
LCP	5%	$En_{53}Wo_{2.3}$
HCP (augite)	5%	$En_{37.7}Wo_{42.4}$
Chlorapatite	1.9%	Phosphate
Merrillite	0.7%	Phosphate
Troilite	2.4%	Fe Sulfide
Pentlandite	0.2%	Fe,Ni Sulfide

Knowledge of the spatial distribution of GRA 06128/9-like lithologies among the asteroid population is critical to understanding the origin and significance of these unique meteorites. We have previously identified two brachinites-like asteroids based on the dominance of FeO-rich OLV absorptions in their visible, near-infrared telescopic spectra [4]. Here we examine the spectra of GRA 06128/9 in the laboratory to determine their spectrally diagnostic characteristics, which likely include both FeO-rich OLV and PLG. As discussed below, the combination of PLG and iron enrichment in GRA 06128/9 relative to the brachinites, may allow us to distinguish between them and thereby identify both the partial melts and their residues.

Spectral Characteristics: Visible, near-infrared spectroscopy provides a critical link between the detailed geochemical insights obtained from meteorites and the distribution of their asteroidal sources, which can be surveyed telescopically [*e.g.*, 5]. To identify asteroids with compositions similar to GRA 06128/9, we must first determine which of its characteristics are spectrally diagnostic and then assess their uniqueness.

Most major near-infrared absorptions in mafic silicates are due to electronic transitions of Fe^{2+} in distorted M1 and M2 crystallographic sites [6]. PLG is abundant (>75%) in GRA 06128/9 and even with 0.07-0.12 wt.% FeO [1], its spectrum likely includes a broad Fe^{2+} absorption near 1.25 µm [6]. However, PLG is largely transparent at other near-infrared wavelengths. This bright matrix could therefore allow minor phases such as OLV to be spectrally amplified.

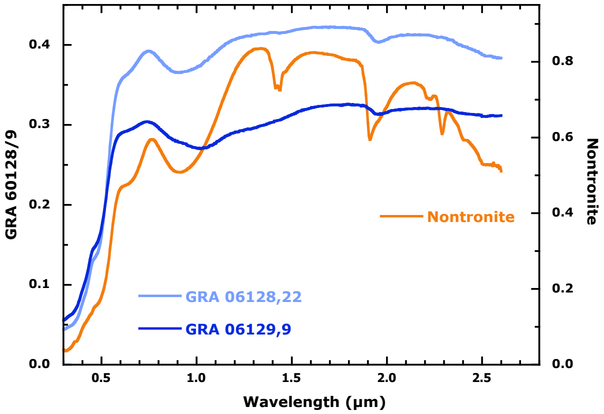

***Fig. 1**: Spectra of GRA 06128/9 and a terrestrial nontronite, one possible weathering component.*

Using the wavelength region (~0.3 to 2.6 µm) covered by visible [*e.g.*, 7] and near-infrared [*e.g.*, 8] telescopic surveys, we measured the same powders of GRA (06128,22 and 06129,9) used for geochemical analysis [1, 2]. After crushing to ≤50 µm, the bidirectional (i=30º, e=0º) reflectance spectra of these samples were measured at Brown University's Keck-NASA Reflectance Experiment Laboratory (RELAB) facility. Although other spectral features indicative of primary mineralogy are present, not surprisingly, the spectra of GRA 06128/9 (**Fig. 1**) also show significant evidence of terrestrial alteration. This alteration is broadly consistent with the spectrum of nontronite ($Na_{0.3}Fe_2(Si,Al)_4O_{10}(OH)_2{\cdot}nH_2O$) or a closely related clay mineral, but is likely to be more complex.

Terrestrial Alteration: The GRA 06128/9 meteorites, found in Antarctic ice, are extensively rusted with pervasive alteration appearing as rusty deposits at grain boundaries or in cracks (**Fig. 2**). Gypsum and bassanite have been tentatively described on the exterior portions of GRA 06128, while Fe sulfates and oxides have been reported within cracks [3]. These meteorites are also heavily oxidized with ~20% of iron existing as nano-phase iron oxide, based on Mössbauer data [9]. Na-rich feldspars are susceptible to weathering under hydrous conditions [10] forming kaolinite and smectite clay minerals [11]. Although clay minerals have not been individually identified in these meteorites, one possible weathering product, given the abundance of oligoclase and oxidized nano-phase iron, is the smectite nontronite, as implied from the spectra (**Fig. 1**).

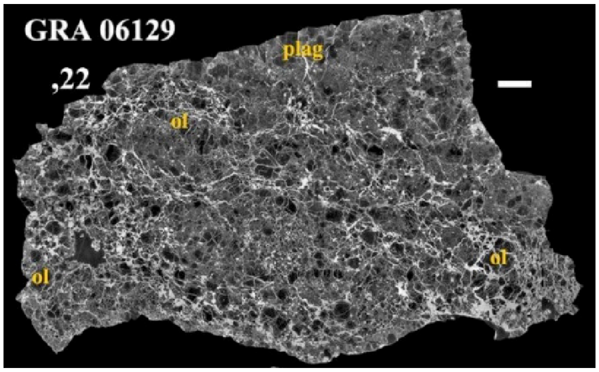

***Fig. 2**: Example of the cracks and in-filled terrestrial alteration that is pervasive in the GRA 06128/9 meteorites. Scale bar is 1 mm.*

Seeing Through the Alteration: This terrestrial alteration presents a significant challenge to defining the inherent spectral characteristics of GRA 06128/9. The two samples measured (**Fig. 1**) show different degrees of alteration, with the spectrum of GRA 06128,22 containing a more significant nontronite-like component. However the spectrum of GRA 06129,9 also includes absorption features beyond 1.0 μm (*i.e.*, at longer wavelengths than those in nontronite), which are broadly consistent with both PLG and OLV — primary mineralogies in these meteorites.

Nonetheless, we are now pursuing two paths to reduce the effects of alteration. First, we are identifying and hand separating minimally altered sample fragments and subjecting them to mild acid leaching. In parallel, we are also attempting to sample and spectrally measure the alteration phase directly. Using spectral modeling, we will then remove the spectral signatures of alteration from the current measurements of GRA 06128/9 and from any residual alteration in the new hand separated and leached samples.

Finding the Crust and the Residue? Based on this preliminary work, it seems likely that the visible, near-infrared spectrum of the GRA 06128/9 meteorites are in fact unique. The presence of PLG and OLV evident in the spectrum of GRA 06129,9 (even with the effects of alteration) is not observed in the spectra of other meteorites. Furthermore, as with the brachinites, the OLV should have relatively long-wavelength absorptions and relative band strengths diagnostic of FeO-rich meteorites and asteroids [4].

However, can we spectrally distinguishing GRA 06128/9 crustal lithologies from their brachinite-like counterparts? While PLG has a distinct 1.25 μm absorption, it readily disappears after disordering from impact shock [12] and was seen remotely, for the first time, only with current lunar missions [13, 14]. In igneous melts of basaltic asteroids (*e.g.*, Vesta), PLG occurs with significant amounts of pyroxene, which also has absorptions in the 1.2 μm region that dominate those in PLG [15]. This is not the case for GRA 06128/9. Furthermore while both are FeO-rich, the OLV in these oxidized partial melts have higher FeO content than the residue (Fo_{40} vs. Fo_{60}). This relative difference is spectrally distinguishable [16]. Finally, the increased PLG content in GRA 06128/9 vs. the brachinites will increase their visible albedos, making it possible to detect smaller crustal fragments.

GRA 06128/9-like lithologies likely occur near previously identified brachinites-like asteroids [4] or those not yet discovered. It is possible that these bodies themselves contain some melt, or that the break-up of a parent-body will produce a family of asteroids including both crustal- and residue- rich fragments. If a geologic context among the asteroid population can be identified for the GRA 06128/9 meteorites, it would constrain the scale of igneous processing both on the parent body (global vs. localized deposit) and throughout the asteroid belt (*e.g.*, oxidation gradients).

References: [1] Day *et al.* (2009) *Nature,* **457**. [2] Day *et al.* (2009) *LPSC 40*, this vol. [3] Zeigler *et al.* (2008) *LPSC 39.* [4] Sunshine *et al.* (2007) *MAPS*, **42**. [5] Gaffey *et al.* (2002) *Asteroids III.* [6] Burns (1993) *Crystal Field Theory.* [7] Bus & Binzel (2002) *Icarus*, 158. [8] Rayner *et al.* (2003) Astron. Soc. Pac., **805**. [9] Treiman *et al.* (2008) *LPSC 39.* [10] Huang & Kiang (1972) *Am. Min.* **57**. [11] Rodgers & Holland (1979) *Geology,* **7**. [12] Adams *et al.* (1979) *LPSC 10.* [13] Matsunaga *et al.* (2008), *GRL* ***35***. [14] Pieters, *et al.* (2009) *LPSC 40*, this vol. [15] Klima *et al. (2007) MAPS*, **42**. [16] Sunshine & Pieters (1998) *J.G.R*, **103**.