MAKING EVOLVED MELTS ON ASTEROIDS. K. G. Gardner-Vandy, T. J. McCoy, and E. S. Bullock, Division of Meteorites, Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119. Email: Gardner-VandyK@si.edu.

Introduction: Until recently, it was understood that a planet-sized, fully differentiated body was required to generate evolved melt compositions. For example, crystal fractionation in a magma ocean setting yielded anorthosites on the Moon, and partial melting of subducted oceanic crust results in andesitic rocks on Earth. Recently, the Mars Science Laboratory rover Curiosity discovered a rock, “Jake_M”, that is a mugaertie, an alkaline igneous rock that could have formed from magmas generated through melting of enriched sources on Mars [1].

There does exist, however, two peculiar meteorites that challenge the requirement of these complex geological processes on planet-sized bodies to generate evolved melt compositions. Graves Nunataks (GRA) 06128 and 06129 are paired achondrite meteorites with mineralogy dominated by olivoclase (~71-90 vol. %, Alb63,85) with minor FeO-rich mafic silicates (olivine (Fa95), high-Ca pyroxene, and low-Ca pyroxene),apatite, merrillite, troilite, pentlandite, spinel and ilmenite [2]. The measured bulk composition and calculated compositions of [3] for GRA 06128/9 plot within the andesite and trachy-andesite fields on the total alkali and silica (TAS) diagram (Fig. 1; [4]). [3] hypothesize that GRA 06128/9 formed by single-stage partial melting of an oxidized precursor, but, until now, that hypothesis had no support, particularly owing to the fact that this formation mechanism conflicts with our current understanding of the geologic setting required for this composition.

An important clue in understanding the mystery of GRA 06128/9’s formation resides in its oxygen isotopic composition, which is nearly identical to the brachinites, primitive achondrites that also have FeO-rich silicates (Fa32,36) and represent partial melt residues [5,6]. [6] explored the formation of the brachinites experimentally and determined that partial melting of R chondrite LaPaz Ice Field (LAP) 03639 at 1250 °C and an fO2 of IW-1 resulted in ~28% partial melting and a residue with mineralogy and compositions like the brachinites (Fa32,36). [6] also ran experiments at an fO2 of IW and IW+1 to extend the experimental space to include the formation conditions of GRA 06128/9 calculated by [2]. Although the melt composition generated in these experiments trend toward the bulk composition of GRA 06128/9, they did not match, nor did the residue composition correspond with the brachinites [6]. In that study, [6] determined that experimental exploration of low-degree melting would be required. It is important to note that [6] recognize the limitations of the R chondrites as the parent material to the brachinites due to their oxygen isotopic differences and hypothesize that the parent material was R chondrite-like in mineralogy and mineral composition.

It is also important to note that the early crystallization ages of GRA 06128/9 and the brachinites and the lack of oxygen isotopic homogeneity of the brachinites make it likely they came from an asteroid-sized body [5,7]. [8] speculated on the possible parent bodies of the R chondrites and brachinites and found A-asteroids 289 Netetta and 246 Asporina to be the best match. The provenance of both GRA 06128/9 and the brachinites raises question about how such an evolved composition could form on an undifferentiated or only partially differentiated asteroid.

We embarked on the following experimental study: 1) to explore the possibility that GRA 06128/9 represents a partial melt composition complementary to a brachinite residue, and 2) to determine if evolved melt compositions can form on asteroid-sized bodies.

Experimental Technique: We performed a partial melting experiment of R4 chondrite LAP 03639 at 1100 °C. The experiment was run on a 143 mg chip for four hours in a Deltech vertical tube furnace at an fO2 of IW, held constant with a CO+CO2 gas mixture. Our starting composition is the same as those in [6]. We based our run temperature on the eutectic temperature of the Ab-SiO2-Fe system (1098 °C) ([9]) and the Ab-SiO2-Fa system (980 °C) ([10]) due to the sodic nature of the plagioclase in GRA 0128/9, the plagioclase-rich composition of the eutectic, and the high FeO content of the olivine in GRA 06128/9 and the brachinites. The fO2 was chosen based upon previous calculations by [2] on the formation conditions of GRA 06128/9. We ran the experiment long enough to achieve melting but retain volatile elements such as Na and K in the melt. The experiment was analyzed at the National Museum of Natural History with an FEI Nova NanoSEM and a JEOL 8900R electron microprobe. Conditions for electron microprobe analysis were: 15 kV accelerating voltage, 20 nA beam current and 5 μm spot size.

Results: The experiment resulted in low-degree melting of the starting material, such that only a portion of the plagioclase and pyroxene melted. Silicate melting reached up to ~1-2 vol. %, with total partial melting reaching up to ~3 vol. % including Fe,Ni-oxides and sulfides. The texture of the experimental charge shows melts pooling interstitial to grains and along grain boundaries on the μm-scale. The average composition of the melt generated is given below (Table 1) with the bulk composition of GRA 06128/9, calculated by [11] based on modal recombination. The two compositions are identical.
The melt composition generated here is also shown on the TAS diagram of [3] (Fig. 1). It resides in the field of the measured and calculated composition of GRA 06128/9 [3].

A conundrum arises when chemically analyzing the composition of GRA 06128/9-type melts in an applicable phase space. The more widely-cited An-SiO$_2$-Fo system is inappropriate due to 1) the sodic nature of the feldspar in GRA 06128/9, and 2) the high FeO content of the olivine in GRA 06128/9 and the related brachinites. [6] showed previously that the products of 1250 °C R chondrite melting experiments did not plot with GRA 06128/9 in Ab-SiO$_2$-Fo space. A more realistic view of the chemical nature of the compositions applicable to the formation of GRA 06128/9 and the brachinites is the NaAlSiO$_4$-FeO-SiO$_2$ system (Fig. 2). The eutectic temperature in the Ab-SiO$_2$-Fo portion of the diagram (top pseudo-ternary) is 980 °C, much lower than in more Mg-rich systems. The melt composition generated here (red dot in Fig. 2) plots on the Ab-Fa join on a 1100 °C isotherm. We plotted the melt composition on this ternary following the methodology of [12]. It is likely that the most applicable phase space is one intermediate between the Ab-SiO$_2$-Fo and Ab-SiO$_2$-Fa ternaries.

MELTs modeling of the average melt composition results in a product with 88% feldspar (Ab$_{89}$An$_{3}$), 8% olivine (Fa$_{50}$), 2% nepheline and 2% liquid. To first order, these mineral abundances and compositions are in line with GRA 06128/9.

Discussions: We have demonstrated that GRA 06128/9 can be generated from low-degrees of melting of an R chondrite-like precursor in a system that is intermediate between the Ab-SiO$_2$-Fo and Ab-SiO$_2$-Fa systems. [13] has shown that melts from low degrees (~2%) of partial melting can migrate from their source regions on a ~100 km asteroid efficiently, so it is likely that the low-degree melts generated here could form an interconnected network at depth on the parent body.

Based on these results, GRA 06128/9 represent the evolved melt composition complementary to a brachinite-like olivine-rich residue. These meteorites are products of partial melting on an FeO-rich chondritic body, similar in mineralogy and mineral compositions to the R chondrites. This is the first set of complementary evolved melts and olivine-rich residues we have in the meteorite collection.

Our experimental study confirms that evolved melts can be formed early in the Solar System’s history on an asteroid-sized body through low-degree melting of an oxidized, volatile-rich chondritic precursor. These extraordinary conditions challenge our preconception that evolved melts formed only on large, planet-sized bodies.