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Letter

A unique glimpse into asteroidal melting processes in the early solar system from the Graves Nunatak 06128/06129 achondrites

C.K. Shearer,[1,*] P.V. Burger,[1] C.R. Neal,[2] Z. Sharp,[3] L.E. Borg,[4] L. Spivak-Birndorf,[5] M. Wadhwa,[5] J.J. Papike,[1] J.M. Karner,[1] A.M. Gaffney,[4] J. Shafer,[2] B.P. Weiss,[6] J. Geissman,[3] and V.A. Fernandes[7]

[1]Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, U.S.A.
[2]Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, Indiana 46556, U.S.A.
[3]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, U.S.A.
[4]Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California 94550, U.S.A.
[5]School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, U.S.A.
[6]Department of Earth, Atmosphere, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, U.S.A.
[7]Berkeley Geochronology Center, Berkeley, California 94709, U.S.A.

Abstract

The recently recovered Antarctic achondrites Graves Nunatak 06128 and 06129 are unique meteorites that represent high-temperature asteroidal processes in the early solar system never before identified in any other meteorite. They represent products of early planetesimal melting (4564.25 ± 0.21 Ma) and subsequent metamorphism of an unsampled geochemical reservoir from an asteroid that has characteristics similar to the brachinite parent body. This melting event is unlike those predicted by previous experimental or geochemical studies, and indicates either disequilibrium melting of chondritic material or melting of chondritic material under volatile-rich conditions.

Keywords: Achondrites, brachinites, planetesimal melting, asteroids, Al-Mg chronometer

Introduction

Achondritic meteorites commonly represent remnants of magmatic systems from differentiated planets (e.g., Moon, Mars) or asteroids (e.g., 4 Vesta). They may be products of early whole planetary body melting such as the lunar ferroan anorthosites, residuum of low degrees of melting and melt extraction such as the acapulcoites and lodranites, or products of episodic mantle partial melting such as lunar and Martian basalts. Newly discovered paired achondritic meteorites Graves Nunatak (GRA) 06128 and 06129 are mineralogically distinct from all of the other known achondrites and do not fit within the planetary or petrologic context of any known parent body. Specifically, these meteorites have a high abundance of sodic plagioclase and Fe-rich silicates, implying they have experienced more elemental fractionation and are more "evolved" than other planetary lithologies such as basalts from the Moon, Mars, or 4 Vesta. Superimposed on this distinct high-temperature mineral assemblage is a high-temperature metamorphism and low-temperature alteration. As discussed below, these unique characteristics are inferred to result from asteroidal processes in the early solar system unlike those recorded in any other meteorites of asteroidal or planetary origin.

Sample description

Paired meteorites GRA 06129 and GRA 06128 (hereafter, GRA) exhibit a heterogeneous, granoblastic texture (Fig. 1) with a modal mineralogy dominated by sodic plagioclase (~81 vol%). The plagioclase exhibits a limited range in composition from $An_{16}Ab_{82}Or_2$ to $An_{13}Ab_{85}Or_2$. Two pyroxenes (orthopyroxene and Ca-rich clinopyroxene) and olivine are the most abundant silicates after plagioclase, making up approximately 9 and 8% of the rock, respectively. The composition of olivine is fairly homogenous at $Fo_{41–40}$ and Cr_2O_3 values from 0.00–0.07 wt%. One olivine grain, adjacent to a spinel, has slightly higher Fo ($Fo_{45–42}$) and Cr_2O_3 (0.02–0.31 wt%) contents, suggesting this compositional variability is related to subsolidus re-equilibration with the adjacent spinel grain. Olivine contains inclusions of Fe-Ni metal, troilite, and pentlandite. Troilite and pentlandite are commonly intergrown with small blobs or blades of Fe-Ni metal (64–68 wt% Ni), spatially associated with the pentlandite. These inclusions appear to be trapped sulfide melt that has undergone subsolidus re-equilibration. The high-Ca pyroxene ranges in composition from $En_{39}Fs_{16}Wo_{45}$ to $En_{44}Fs_{29}Wo_{27}$. Most pyroxene grains exhibit exsolution of low-Ca pyroxene lamellae that are 2 to 8 μm in width. The average composition of the orthopyroxene is $En_{53}Fs_{45}Wo_2$. Based on the stoichiometry of ~100 electron microprobe analyses, the average ferric iron ($Fe^{3+}/Fe^{3+}+Fe^{2+}$) in the high-Ca pyroxene is 7%. Apatite overgrowths on merrillite (dehydrogenated whitlockite) occur in individual phosphate masses up to 600 μm in size. Apatite is halogen-rich (Cl ~5.0 wt%, F ~0.7 wt%), whereas the merrillite is halogen-poor with substantial Na in the CaIIA site (~2.5%). The modal abundance of phosphates is ~1.0%. Ilmenite and "spinel" are commonly intergrown and are distributed throughout the section in trace abundances.

A megascopic view of the GRA meteorites indicates they

* E-mail: cshearer@unm.edu

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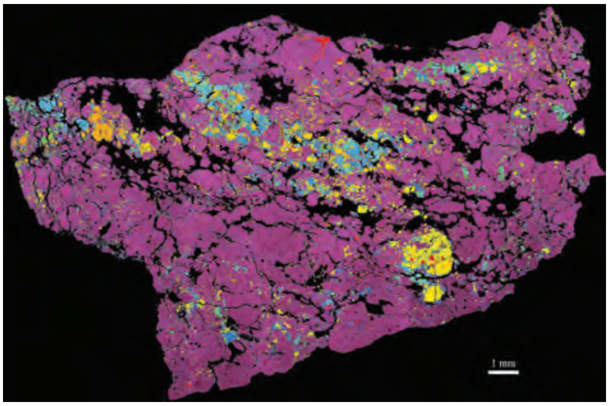

FIGURE 1. False color backscattered-electron composite image of thin section GRA 06129,23. Purple = plagioclase, blue = orthopyroxene and clinopyroxene, orange-yellow = olivine, blue-green = phosphates, red = Fe-bearing oxides, sulfides, and metals.

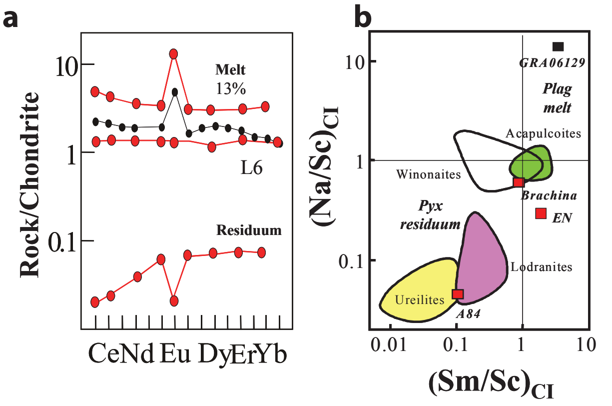

FIGURE 2. (**a**) REE content of GRA 06128/129 (black points) compared to the REE patterns of an L6 chondrite, a sodic-rich melt pocket produced after 13% melting of a L6 chondrite (Feldstein et al. 2001), and a residuum produced after extraction of a 13% melt from L6 (all in red points). The modal mineralogy of that residuum is 1% cpx, 30% opx, and 45% olivine (Feldstein et al. 2001). (**b**) $(Sm/Sc)_{CI}$ vs. $(Na/Sc)_{CI}$ illustrating the relationship between GRA 06129 and primitive achondrites that may represent "asteroidal restites" (after Mittlefehldt et al. 1998). Brachinites are represented by A84 (ALH 84025), EN (Eagles Nest), and Brachina. The quadrant defined by $(Na/Sc)_{CI} < 1$ and $(Sm/Sc)_{CI} < 1$ and designated as pyroxene-bearing residuum (Pyx residuum) potentially represents a field of CI bulk composition with melt removed. The quadrant defined by $(Na/Sc)_{CI} > 1$ and $(Sm/Sc)_{CI} > 1$ and designated as plagioclase normative melt (Plag melt) represents the field of melts removed from a CI bulk composition.

have undergone significant low-temperature alteration. The microscopic view indicates this alteration is pervasive adjacent to mineral surfaces and in fractures within mineral grains. Initial observations indicate at least three types of low-temperature alteration in this meteorite: (1) alteration that primarily consists of Fe-bearing phases; (2) alteration that consists of Fe-rich phases, sulfates, and perhaps sulfides; and (3) alteration of olivine to "iddingsite." It is uncertain to what degree this alteration is parent body vs. terrestrial.

As expected from this unusual mineralogy, the bulk meteorite is high in Al_2O_3 (15.5 wt%), CaO (6.22 wt%), and Na_2O (7.51 wt%). The CaO/Al_2O_3 is 0.40, while the K content is rather low $K_2O/(Na_2O + K_2O)$ wt% = 0.033. The relatively high modal abundance of phosphate is evident in the overall P_2O_5 of the bulk rock (0.19 wt%). Although the high Na content and abundant phosphates imply a formation involving extensive elemental fractionation, the overall trace element characteristics do not support this inference. The GRA whole rock REE pattern (Fig. 2a) is roughly flat (1 to 2× chondrite) with a positive Eu anomaly (5× chondrite). Nickel and Co abundances are relatively high (2215 and 297 ppm, respectively) indicating GRA did not experience extensive amounts of olivine fractionation. Na/Sc and Sm/Sc ratios are higher than CI chondrite (Fig. 2b) and imply this lithology represents the accumulation of plagioclase and phosphates from a silicate melt.

Complete analytical details are in the appendix[1] available as a deposited item.

CONDITIONS OF CRYSTALLIZATION AND METAMORPHISM

Most of the GRA primary igneous textures and mineral compositions have re-equilibrated at subsolidus temperatures. This is reflected in features such as pyroxene exsolution, granoblastic texture, generally homogeneous mineral compositions, and diffusion profiles adjacent to olivine-spinel and spinel-ilmenite interfaces. Nevertheless, some phases, such as olivine and spinel, record equilibrium temperatures of (~900 ± 50 °C) that may approach the temperature of solidification (e.g., Sack and Ghiorso 1991). However, the temperature of pyroxene equilibration is approximately 670 ± 50 °C (Lindsley 1983), consistent with extensive post-crystallization metamorphism. The ferric iron content of pyroxene in GRA implies an oxygen fugacity (f_{O_2}) that is more oxidizing than the Moon (Iron-wüstite [IW]-1) as lunar pyroxenes contain no ferric iron (Papike et al. 1998). Several mineralogical oxybarometers, based on silicate-oxide equilibria and oxide equilibria, predict that re-equilibration occurred at an f_{O_2} between IW + 0.5 and IW + 1.5 (Ghiorso and Sack 1991).

Age of GRA 06128 and GRA 06129

Preliminary phosphate Pb-Pb ages are imprecise but ancient, 4.4–4.6 Ga (Ash et al. 2008), and therefore suggest these meteorites represent a melting event early in the history of the solar system. Planetary differentiation through melting is a fundamental process that occurs early in the history of the solar system. Chronological investigations of planetesimal melting using primitive meteorites indicate that incipient melting occurred as early as 2–5 million years (m.y.) after the formation of CAIs (Wadhwa et al. 2006) and continued until planetary-scale events were recorded on the Moon and Mars from 25 to 250 m.y. (Shearer et al. 2006; Borg and Drake 2005). Magnesium isotopic measurements conducted on a whole rock sample of GRA indicate live ^{26}Al at the time of Al/Mg fractionation in GRA. The

[1] Deposit item AM-08-059, Appendix (analytical details). Deposit items are available two ways: For a paper copy contact the Business Office of the Mineralogical Society of America (see inside front cover of recent issue) for price information. For an electronic copy visit the MSA web site at http://www.minsocam.org, go to the American Mineralogist Contents, find the table of contents for the specific volume/issue wanted, and then click on the deposit link there.

whole rock sample records an radiogenic excess ^{26}Mg (Δ^{26}Mg) of 0.080 ± 0.009‰, and assuming a solar system initial Δ^{26}Mg of 0.032 ± 0.004‰ (Thrane et al. 2006), yields a model initial ^{26}Al/^{27}Al ratio of $2.96 \pm 0.26 \times 10^{-6}$. From this ^{26}Al/^{27}Al ratio, we infer a ^{26}Al-^{26}Mg model age relative to the E60 Efremovka CAI (Amelin et al. 2002) of 4564.25 ± 0.21 Ma. This is most likely the age of GRA plagioclase accumulation and crystallization and is not related to the age of later metamorphism.

Planetary body of origin

Several geochemical and geophysical fingerprints can be used to ascertain the planetary body from which this unique meteorite was derived. Bulk oxygen isotopic analysis of GRA with alteration removed has a Δ^{17}O of –0.21. This value lies below the terrestrial (and lunar) mass fractionation line (TMFL) and is similar to the Δ^{17}O values of angrites, HEDs, mesosiderites, pallasites, and brachinites, indicating GRA could be derived from a similar parent body (Fig. 3a). Estimates of f_{O_2} for GRA are more reducing than many terrestrial environments and yet more oxidizing than the Moon, angrites, HEDs, mesosiderites, and pallasites, which suggests that these bodies are not the source of GRA. The Fe/Mn ratios of mineral phases such as olivine and pyroxene can also be used to determine planetary origins (Karner et al. 2003), however, these systematics are defined by basaltic lithologies with few metamorphic features, unlike GRA. Nevertheless, the Fe/Mn of olivine in GRA overlaps with fields defined for the Earth and brachinites (Fig. 3b). Finally, the ancient age derived from the Al-Mg chronometer indicates this lithology was derived via melting only 2–3 m.y. after the earliest formed materials in the solar system (i.e., CAIs). Wadhwa et al. (1998) determined the Mn-Cr age of Brachina to be 4563.7 ± 0.9 Ma indicating that magmatism on the Brachina parent body was contemporaneous with the inferred crystallization age of GRA. All of these observations are consistent with derivation from the parent body with geochemical characteristics and a thermal history like the brachinite parent body.

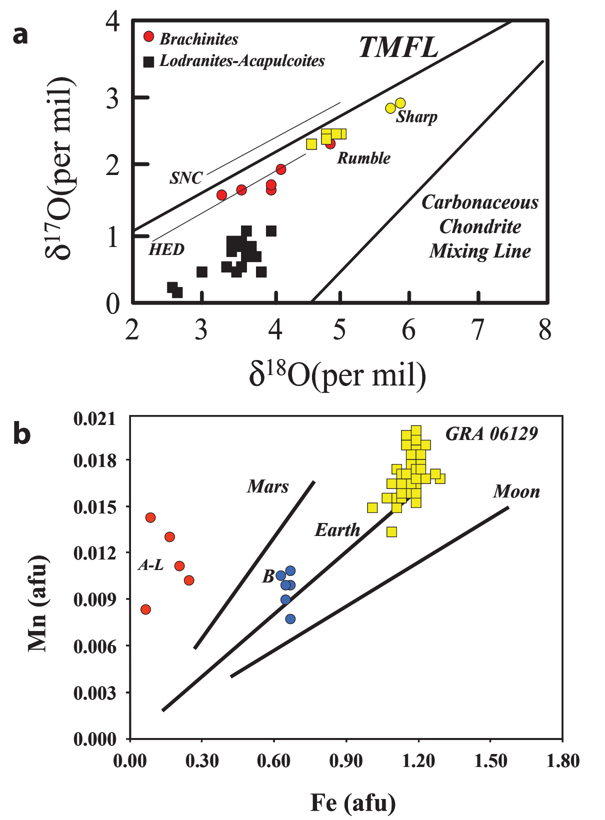

Figure 3. Clues to the planetary origin of GRA 06128/129. (**a**) Oxygen isotopic composition of GRA 06129 (yellow symbols = determined by Rumble, Sharp; see also Zeigler et al. 2008) as compared to other achondritic meteorites, the Terrestrial Mass Fractionation Line (TMFL) and the Carbonaceous Chondrite Mixing Line. (**b**) Fe vs. Mn (afu) of olivine in GRA 06129 (yellow squares) compared with olivine from the Earth, Moon, Mars, (the latter three planets represented by best fit lines through the data of Karner et al. 2003), brachinites (B), and acapulcoites-lodranites (A-L).

Origin of high-temperature assemblage

Unlike GRA, brachinites are relatively fine-grained, olivine-bearing, ultramafic rocks that are similar to dunites and peridotites. Like many other primitive achondrites, the brachinites are thought to have formed by extensive metamorphism of chondritic precursors resulting in varying degrees of melting (e.g., Nehru et al. 1992; Mittlefehldt et al. 1998). Although not all potential compositions that could be extracted from chondritic precursors have been identified in the meteorite collection, chondrite melting experiments indicate that melt compositions ranging from Fe-Ni sulfide melts (at low temperature) to basalts (at higher temperature) can be produced during episodes of asteroidal melting (e.g., Jurewicz et al. 1991). However, none of the melting models that are based on meteorite observations or melting experiments predict the generation of melts capable of producing sodic plagioclase-rich lithologies similar to GRA. Thus, GRA appears to give us a unique perspective of early planetesimal melting.

Sodic plagioclase-rich lithologies are rare in meteorites and models for their origin fit within the context of only a few observations. Minute, rare clasts and fragments containing sodic feldspar have been identified in chondrites and ureilites such as Kaidun, Adzhi-Bogdo, and Dar al Gani 319 (Ikeda and Prinz 2001). Also, sodic plagioclase has been identified in Winonaites (Benedix et al. 1998) and silicate inclusions in IAB irons (Takeda et al. 2000). Many of these studies suggested these lithologies were produced by relatively low degrees of partial melting of a chondritic precursor followed by inhomogeneous segregation and brecciation (Ikeda and Prinz 2001; Benedix et al. 1998; Takeda et al. 2000). Arai et al. (2008) suggested that melting of a volatile-rich, chondrite parent body may produce "andesite" melts rich in normative sodic plagioclase. Chondrite (L6) disequilibrium melting experiments performed by Feldstein et al. (2001) generated melt pockets with compositions similar to GRA.

The petrogenesis of several meteorite groups, such as acapulcoites-lodranites and brachinites, has been closely tied to small degrees of partial melting (e.g., Nehru et al. 1992; Mittlefehldt et al. 1998), although the extent of melt removal and the composition of the missing melt has been a point of substantial debate. Small degree partial melting of an L6 chondrite (Feldstein et al. 2001) produced high-Na and high normative-plagioclase melts with REE patterns similar to GRA (Fig. 2a). Melting of a

CI chondrite would drive a melt composition to both high $(Na/Sc)_{CI}$ and $(Sm/Sc)_{CI}$, and thus could possibly account for these characteristics of GRA (Fig. 2b). If this scenario is correct, the low (chalcophile element/Sc)$_{CI}$ ratio of GRA could reflect production, segregation and removal of a lower temperature sulfide melt from the silicate melt prior to crystallization. The small melt fractions required in this model appear to be analogous to melting processes envisioned for lodranites (Mittlefehldt et al. 1998). GRA itself does not represent a melt composition, but most likely represents the accumulation of plagioclase from such a melt. Accumulation of plagioclase during magmatic processes on a small asteroid is possible and is illustrated by the cumulate eucrites that presumably formed on 4 Vesta. The plagioclase accumulation mechanism on the GRA parent body was more efficient than that for the cumulate eucrites (modal plagioclase = 35–40%) and approaches the plagioclase accumulation process that produced the lunar ferroan anorthosite crust (plagioclase > 95%).

As an alternative to low degrees of partial melting, GRA could represent an asteroidal crust produced by plagioclase accumulation either during global planetary differentiation (i.e., magma ocean) (Zeigler et al. 2008) or crystallization of a large magma body (i.e., layered intrusion). The magnetic properties of GRA suggests that the GRA parent body may have been large enough to have generated an internal magnetic field, this could indicate high degrees of planetary melting that could have led to the formation of a metallic core. The global differentiation model would be analogous to the lunar ferroan anorthosites that were produced during the initial stages of differentiation by plagioclase flotation in a magma ocean (e.g., Shearer et al. 2006). Although planetary bodies the size of the Moon and smaller are more likely to have primary plagioclase crust during planetary differentiation, due to pressures regimes under which a magma ocean would have crystallized, spectral analysis of over 100 asteroids does not hint at crusts dominated by plagioclase (Bell et al. 1989). Even more damaging to this hypothesis is that crystallization of a magma ocean with chondritic bulk composition will not produce sodic plagioclase. For example, differentiated asteroid 4 Vesta, which is thought to have experienced differentiation via a magma ocean (Righter and Drake 1997), contains a basaltic crust and not a plagioclase-rich crust. It is also unlikely that a layered intrusion on an asteroid could produce a late-stage lithology that is as depleted in incompatible elements as GRA. Plagioclase-enriched cumulates produced via crystallization of asteroidal basalts (cumulate eucrites) have similar REE patterns to GRA, but have significantly more calcic plagioclase ($An_{93}Ab_6Or_{0.5}$ to $An_{72}Ab_{26}Or_2$). Therefore, the most plausible mechanism to produce GRA is through small degrees of partial melting of a chondritic parent body followed by accumulation of plagioclase and phosphates.

In conclusion, the GRA achondrites provide a perspective of planetesimal processes during the earliest stages of solar system history that are unrecorded in any other meteorite. These meteorites indicate that the very earliest stages of planetesimal melting that were partially driven by the decay of short-lived radionuclides, do not necessarily yield basaltic melts. This is contrary to the commonly held view that the earliest melting on planetary bodies (from 10 to 30 m.y.) was basaltic in nature.

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