

**CLUES TO THE FORMATION OF PV1, AN ENIGMATIC CARBON-RICH CHONDRITIC CLAST FROM THE PLAINVIEW H-CHONDRITE REGOLITH BRECCIA.** Alan E. Rubin, Josep M. Trigo-Rodriguez, Takuya Kunihiro, Gregory W. Kallemeyn, and John T. Wasson, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA. (aerubin@ucla.edu)

Chondritic clast PV1 from the Plainview H-chondrite regolith breccia is a subrounded, 5-mm-diameter un-equilibrated chondritic fragment that contains 13 wt.% C; the carbon is poorly graphitized and occurs mainly within irregularly shaped 30-400- $\mu\text{m}$ -size opaque patches [1-4]. Three similar C-rich chondritic clasts in other H-chondrite regolith breccias have been found: DT1 and DT2 from Dimmitt and WN1 from Weston [2,5]. The clasts are enigmatic for two principal reasons: (1) they appear to lack the fine-grained silicate-rich matrix material [2-5] that occurs in type-3 ordinary chondrites (OC) and carbonaceous chondrites, and (2) their bulk C contents (6-13 wt.%; [2]) are far higher than those in the most C-rich meteorites (e.g., 2.8 wt.% C in CI Orgueil and 4.1 wt.% C in the North Haig ureilite [6]). Our new petrographic observations, SEM studies and previously unpublished INAA data on PV1 combined with literature data directly address these problems and shed new light on the formation of C-rich chondritic clasts.

**PV1 started off as a normal H3 chondrite.** We measured the apparent diameters of 60 chondrules in PV1 (thin section UNM 273) and found a mean apparent diameter of  $310 \pm 120 \mu\text{m}$ , essentially identical to that of mean H-chondrite chondrules ( $300 \mu\text{m}$ ; [7]). Our INAA data show a mean Mg-normalized refractory lithophile abundance ratio (Al, Sc, Ca, La, Ce, Nd, Sm, Eu, Tb, Ho, Yb, Lu) relative to H chondrites of  $1.03 \pm 0.15$ , i.e., indistinguishable from that of mean H chondrites. The O-isotopic composition ( $\delta^{18}\text{O} = 3.35\text{‰}$ ;  $\delta^{17}\text{O} = 2.40\text{‰}$ ;  $\Delta^{17}\text{O} = 0.66\text{‰}$  [3]) is close to mean H4-6 chondrites ( $\Delta^{17}\text{O} = 0.73 \pm 0.09 \text{‰}$ ; [8]). The occurrence of all four known C-rich chondritic clasts in H-chondrite regolith breccias is consistent with derivation from the H-chondrite parent body. It thus seems very likely that PV1 silicates were derived from an H-group chondrite precursor. It is probable that PV1 started off as a type-3 chondrite because of the heterogeneous olivine (mean Fa  $17 \pm 7.7 \text{ mol}\%$ ; PMD = 46) and low-Ca pyroxene (mean Fs  $10.6 \pm 6.3 \text{ mol}\%$ ; PMD = 48) compositional distributions [2] and the presence of glass in some BO and PO chondrules.

**PV1 was impact-melted on the H-chondrite parent body.** If PV1 was initially a normal H3 chondrite, it would have had  $\sim 18 \text{ wt.}\%$  metallic Fe-Ni [6]. Modal analysis indicates that the clast contains  $\sim 6 \text{ vol.}\%$  (i.e.,  $\sim 14 \text{ wt.}\%$ ) metallic Fe-Ni [2]; however, this is an upper limit because some of the metal occurs in veins that might not be indigenous to the clast [2]. Moderate depletion of metallic Fe-Ni in the clast is indicated by the Mg- and H-chondrite-normalized abundance ratios of Fe (0.65), Ni (0.71) and Co (0.44) in the bulk analysis of PV1. Loss of metal requires a high-temperature event wherein temperatures reached or exceeded the Fe-FeS eutectic ( $988^\circ\text{C}$ ). This event is likely to have been impact melting on the

parent body; many impact-melt-rock clasts are significantly depleted in metallic Fe-Ni (which formed a melt that separated from silicate). There is additional evidence for a high-temperature event. Our SEM studies reveal that most interfaces between adjacent chondrules are fused together, rendering PV1 somewhat analogous to a cluster composed of large clumps of compound chondrules. Chondrule fusion indicates that temperatures must have reached or exceeded the solidus temperature for H-chondrite plagioclase (Ab82), i.e.,  $\sim 1120^\circ\text{C}$ . Such an event is consistent with the depletion of moderately volatile lithophile elements in PV1: the Mg- and H-chondrite-normalized abundance ratios of Na and K are 0.72 and 0.69, respectively. PV1 also contains several objects that appear to be melted fine-grained silicate matrix material. This material is more ferroan than most chondrules and, hence, has a lower melting temperature than magnesian olivine. One such object (I5) consists of  $\sim 20 \text{ vol.}\%$  small ( $1\text{--}17 \mu\text{m}$ ) metallic Fe-Ni and sulfide grains,  $\sim 50 \text{ vol.}\%$  small ( $0.5\text{--}3 \mu\text{m}$ ) silicate grains, and  $\sim 30 \text{ vol.}\%$  pore space that is presently filled with C-rich material. The apparent absence in PV1 of fine-grained silicate-rich matrix material is a consequence of the melting and recrystallization of this material.

**PV1 was fractured, aqueously altered, enriched in C, and faulted.** *Fracturing.* Numerous  $1\text{--}3 \mu\text{m}$ -thick,  $20\text{--}160 \mu\text{m}$  long, cross-cutting fractures transect every chondrule in the PV1 clast. Such fracturing is almost certainly due to crushing caused by an impact event. It appears that this fracturing event involved little melting and, hence, was not the same event that caused impact melting of the clast. Fracturing probably post-dated impact melting. *Aqueous alteration.* In amoeboid olivine inclusions in CO3.2 Kainsaz, forsteritic olivine is rimmed by thin veins of ferroan olivine that conform to the shape and outlines of pre-existing cracks and grain boundaries [9]. PV1 resembles Kainsaz in that numerous fractures in PV1 chondrules are rimmed by ferroan olivine (although in PV1 the ferroan rims are much coarser). In many porphyritic chondrules and chondrule fragments (e.g., C4, D3, K3), relict cores of low-FeO olivine are surrounded by ferroan olivine and hemmed in by fractures. Analogous with the aqueous alteration inferred for CO3 chondrites [9], it seems likely that an aqueous fluid containing Fe, Si and O entered the fractures in PV1 and formed ferroan olivine. However, the inferred aqueous alteration was more extensive in PV1 than in Kainsaz or in type-3 OC. Temperatures were high enough in PV1 to cause  $\text{Fe}^{+2}$  from the new olivine in the fractures to exchange partially with  $\text{Mg}^{+2}$  from adjacent low-FeO olivine in the chondrules to form diffusive haloes of ferroan olivine around the low-FeO olivine cores. Aqueous alteration is probably also responsible for the paucity of Fa0-5 grains in the

olivine compositional distribution of PV1 relative to that of a highly unequilibrated type-3 OC such as LL3.1

**Krymka [2]. Carbon enrichment.** The apparent lack of reaction (i.e., silicate reduction) at the interfaces between C-rich patches and adjacent silicate implies that the PV1 clast acquired its abundant C after the impact-melted clast had cooled. In several places (e.g., F6, I4, K2), the SEM images show bright-shaded veins within the C-rich material that bend in the direction of the faults; this indicates that the C-rich material was emplaced prior to faulting.

**Faulting.** Several faults with a maximum length of ~1.2 mm and a maximum displacement of ~200  $\mu\text{m}$  occur in PV1. The faults are oriented in different directions and cut across (and thus post-date) the chondrule fractures. Because the faults do not penetrate the Plainview host, it is clear that faulting occurred before PV1 was incorporated into its immediate surroundings in Plainview. The impact event that caused the faulting could have been the one that fragmented and dislodged PV1 from its parent rock and deposited it in the final regolith.

**Potential sources of carbon.** Because PV1 was initially a normal H3 chondrite and because type-3 OC contain  $\leq 1$  wt.% C [6], we infer that the clast did not obtain its abundant C during agglomeration in the solar nebula. This conclusion is supported by the petrographic evidence that C enrichment occurred after PV1 was impact melted and cooled. Therefore, PV1 must have acquired its C on the H-chondrite parent body. It is conceivable that the C was derived by outgassing of CO from metamorphosed (H4-6) rocks in the asteroid interior followed by recondensation of C within permeable material near the asteroid surface [10]. In a simplified reaction ( $\text{Fe} + \text{CO} \rightarrow \text{FeO} + \text{C}$ ), oxidation of 10 wt.% Fe would yield ~2 wt.% C. This value is higher than that in type-3 OC, but much lower than that in PV1. If Fe outside the PV1 region were involved in the carbon reduction, then the high C content of PV1 could in principle be explained. Perhaps a more plausible source of C is a C-rich projectile. The most C-rich planetesimal-size projectiles are comets; e.g., the dust-ice fraction of Comet Halley reportedly contains ~19 wt.% C [11], although some estimates of the C contents of comets are lower. Carbon occurs in comets as CO, CO<sub>2</sub>, H<sub>2</sub>CO, CH<sub>4</sub>, HCN, CH<sub>3</sub>OH, CH<sub>2</sub>HOH, CH, organic (CHON) grains, organic refractory coatings on silicate grains and, by analogy with CI and CM chondrites, complex hydrocarbons and kerogen that cannot be detected by remote studies. (The hypothetical comet could also have served as the source of water responsible for the aqueous alteration of PV1.)

It is not unreasonable that a cometary impact could have affected PV1. A small fraction of Jupiter-family comets (JFCs) evolve into near-Earth objects [12] and could impact main-belt asteroids at relative velocities of ~5 km s<sup>-1</sup> (similar to those of average asteroid/asteroid collisions) [13]. Recent studies estimate that ~1% of the projectiles impacting asteroids today are JFCs [14,15].

**Inferred history of PV1.** H3 material residing in the near-surface region of an H-chondrite asteroid was im-

pact-melted; chondrules fused, ferroan fine-grained silicate matrix material was melted, some metal melted and separated from silicate, and the rock was left with numerous impact-induced voids (analogous to porous, melt-bearing fragmental breccias found in impact-crater ejecta deposits [16]). Some time later, a cometary impact occurred, fracturing PV1. An aqueous fluid, possibly derived from recondensed cometary ice, permeated the fractures in the PV1 chondrules, causing the development of ferroan olivine. Carbon from the comet filled the voids in PV1; the carbon was probably transported as a fluid that later broke down into elemental C. The  $\delta^{13}\text{C}_{\text{PDB}}$  composition of PV1 (-21‰ [3]) is within the range reported for comets (-11‰ to -43‰ [17]).

The carbon may have been derived via recondensation of C from CO or, conceivably, from liquid hydrocarbons that flowed into the voids in the clast. The mechanism responsible for enriching PV1 in C is still uncertain. A later impact event (or series of events) caused extensive faulting in the PV1 parent rock, dislodged the PV1 clast and deposited it in the regolith. Annealing of the Plainview host and its PV1 inclusion at temperatures near 400°C [4] caused the graphitizable organic C in PV1 to pyrolyze and graphitize, thereby transforming it into poorly graphitized C.

Some of the C-rich aggregates that occur in the relatively C-rich type-3 OC (e.g., Sharps, ALHA77011) may have been derived from disrupted C-rich chondritic clasts similar to PV1 [5]. However, the abundant metallic Fe-Ni and minor chromite in most C-rich aggregates [3,4] indicate different sources or more complex histories.

**References:** [1] Fodor and Keil (1976) *GCA*, 40, 177-189; [2] Scott et al. (1981) *EPSL*, 56, 19-31; [3] Scott et al. (1988) *PLPSC*, 18<sup>th</sup>, 513-523; [4] Brearley (1990) *GCA*, 54, 831-850; [5] Scott et al. (1981) *Nature*, 291, 544-546; [6] Jarosewich (1990) *Meteoritics*, 25, 323-337; [7] Rubin (2000) *Earth-Sci. Rev.*, 50, 3-27; [8] Clayton et al. (1991) *GCA*, 55, 2317-2337; [9] Chizmadia et al. (2002) *MPS*, 37, 1781-1796; [10] Sugiura et al. (1986) *EPSL*, 78, 148-156; [11] Jessberger et al. (1988) *Nature*, 332, 691-695; [12] Levison and Duncan (1997) *Icarus*, 127, 13-32; [13] Campins and Swindle (1998) *MPS*, 33, 1201-1211; [14] Wetherill (1978) In *Asteroids: An Exploration Assessment*, NASA CP 2053, 17-35; [15] Rpt. NEO Sci. Def. Team (2003), 154 pp.; [16] Stöffler et al. (1980) *Proc. Conf. Lunar Highlands Crust*, 51-70; [17] Wyckoff et al. (2000) *Ap. J.*, 535, 991-999.