Pecora Escarpment (PCA) 91007

Vesicular Eucrite, 223.6 grams

Antarctic Find

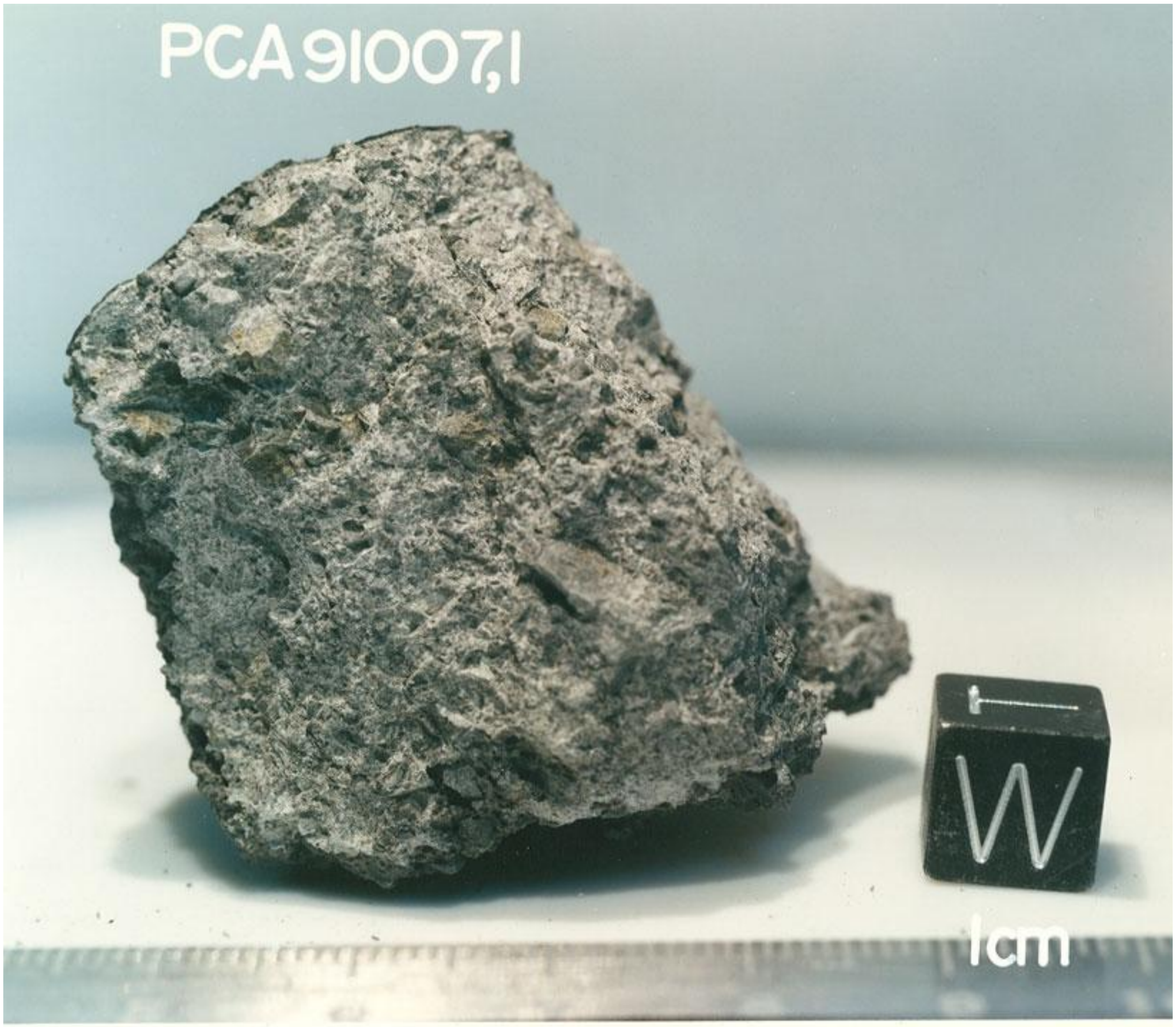

Figure 1*: View of PCA 91007 in the Meteorite Processing Lab at NASA-JSC. The cube edges are 1 cm in length.*

Introduction: The PCA 91007 meteorite (**Figure 1,2**) was collected from the main ice field of the Pecora Escarpment in Central Antarctica during the 1991 ANSMET field season (Grossman, 1994). It was first reported as a eucrite in volume 15, issue 2 of the Antarctic Meteorite Newsletter, which noted its weight (223.6 grams), dimensions (6.8 cm x 4.8 cm x 4.5 cm), weathering (minor to moderate rustiness with haloes and stains, as well as visible evaporite minerals), and fracturing character (minor). A macroscopic description at JSC reported a shiny, black fusion crust covering 40% of the meteorite, with abundant green crystals and minor metal set in a gray matrix (Antarctic Meteorite Newsletter 15/2). It is uniformly fine-grained (e.g., B. Mason *in* Antarctic Meteorite Newsletter 15/2; Warren et al, 1996b, 1996c, 2009), even though the original macroscopic description noted the

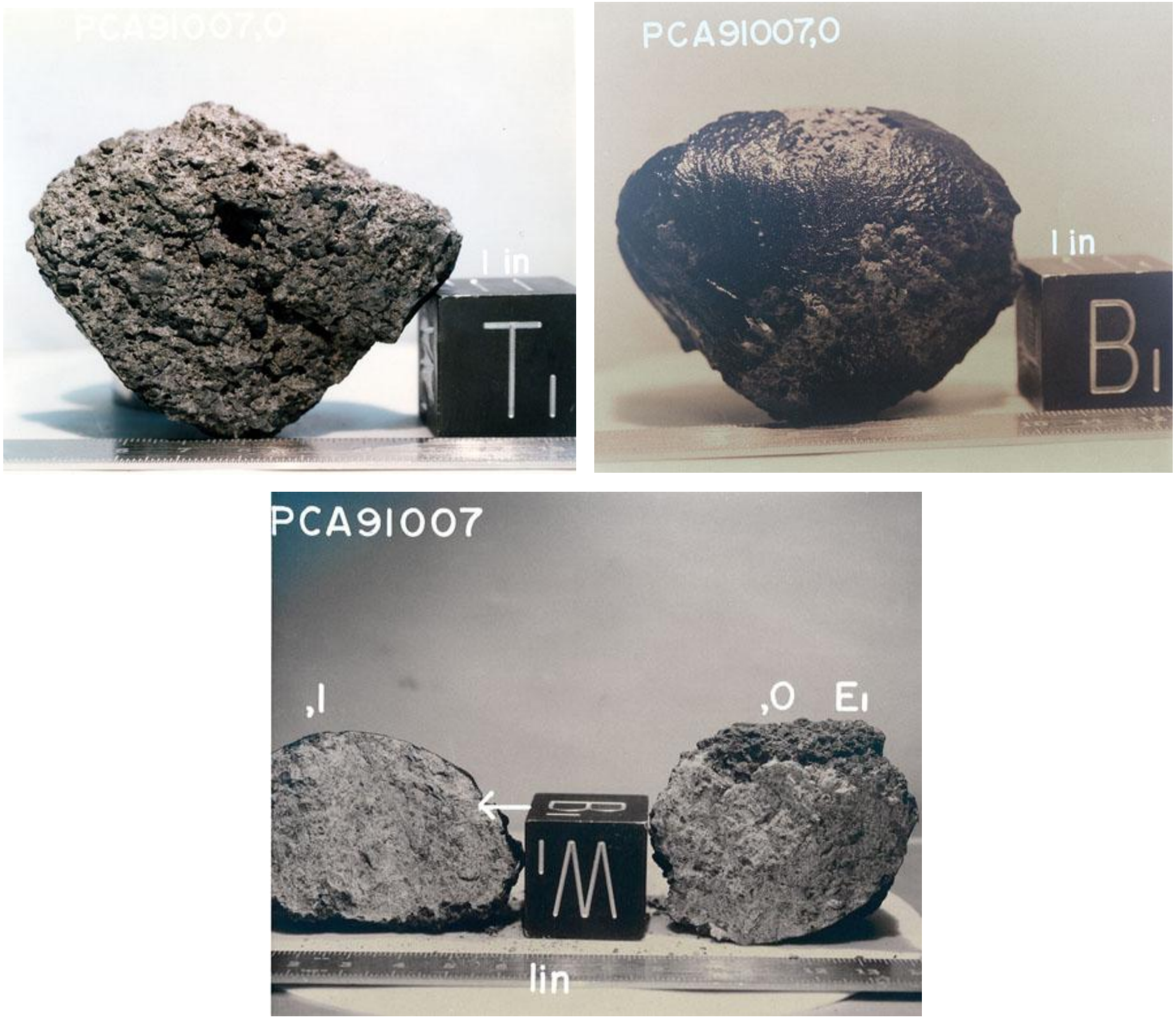

Figure 2*: Top, bottom, and cut views of PCA 91007. The bottom view (top right) clearly shows the glossy back fusion crust. The cube edges are 1 cm in length. From the NASA-JSC Meteorite Curation website, at http://curator.jsc.nasa.gov/antmet/samples/petdes.cfm?sample=PCA91007.*

"medium to coarse-grained" nature of its matrix (C. Satterwhite *in* Antarctic Meteorite Newsletter 15/2). PCA 91007 was later reclassified as a brecciated eucrite (Antarctic Meteorite Newsletter 17/1; Grossman, 1994); however, there is only limited textural evidence for brecciation (Warren et al, 2009), and thus has been referred to as "nearly" unbrecciated (Warren et al, 1996b, 1996c). It has also been referred to as a polymict eucrite (e.g., Warren et al, 2009).

The most unique feature of PCA 91007 is the presence of numerous, small, spherical vesicles that make up ~0.4 vol% of the meteorite (McCoy et al, 2006). This places PCA 91007 in a unique category of vesicular eucrites; other members of this classification include the well-studied eucrite Ibitira, two

Antarctic meteorites (Y-981651 and PCA 82502, the latter of which may be a pair of PCA 91007), and a single specimen from Northwest Africa, NWA 1240 (Barrat et al, 2003; Warren et al, 2009). Anomalous oxygen isotopic compositions in PCA 91007 also suggest a parent body other than Vesta (Scott et al, 2009).

General Petrography: No summary of modal or normative mineralogy has yet been reported for PCA 91007. It is a fine-grained aggregate of ≤0.5-mm granular to acicular pyroxene and ≤0.3 mm-long acicular plagioclase needles, with pyroxene present in twice the abundance of plagioclase (Antarctic Meteorite Newsletter 15/2; Warren et al, 1996b, 1996c; **Figure 3**). Average grain sizes are on the order of 0.05-0.1 mm, which is more uniformly fine-grained than most eucrites, suggestive of quenching (Warren et al, 1996b, 1996c). Some regions of the meteorite are truncated by deformation surfaces (Scott et al, 2009) but the original texture has been preserved; as mentioned above, PCA 91007 is generally unbrecciated, with some limited evidence of brecciation (Warren et al, 2009).

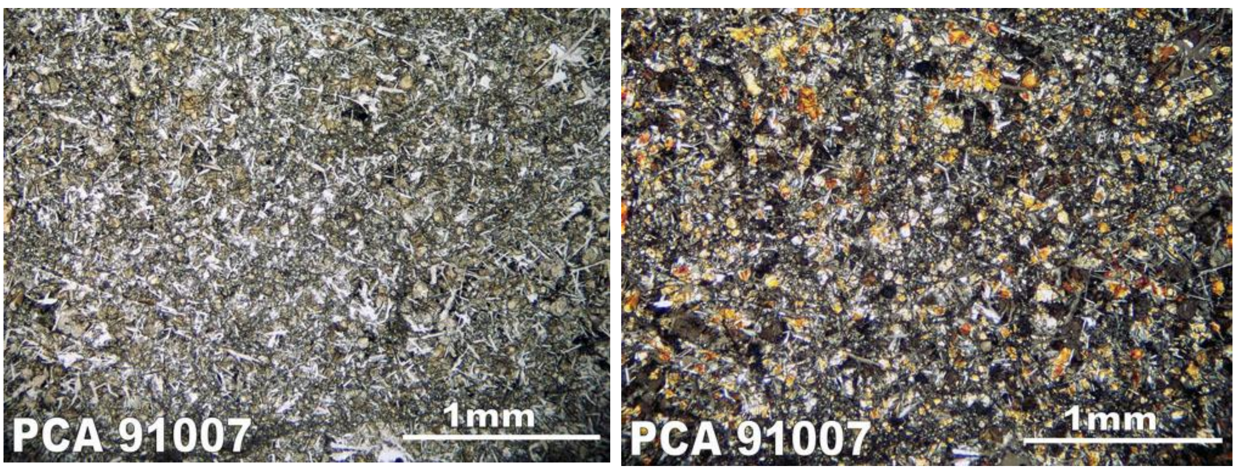

***Figure 3**: Plane-polarized light (top) and cross-polarized light (bottom) views of a PCA 91007 thin section, with fine-grained, granular to acicular pyroxene and acicular plagioclase. From the NASA-JSC Meteorite Curation Website, same source as in **Figure 2**.*

Vesicles: The vesicular nature of PCA 91007 was first reported in Warren et al (1996b, 1996c). They found 5-8 vesicles in a small (5 mm^2) thin section, with diameters of 50-150 µm. An X-ray Computed Tomography (CT) study of PCA 91007,0 (with a sample volume of 34.5 cm^3) revealed 787 total vesicles in the section, ranging from 0.1-4 mm^3 (median = 0.095 mm^3) consisting of 0.4 vol% of the sample; this results in a vesicle density of 22.81/cm^3 (McCoy et al, 2006; **Figure 4**). The size, density, and volume fraction of these vesicles are significantly smaller in PCA 91007 than Ibitira (McCoy et al, 2006), but are similar to another fine-grained, vesicular sample collected in the same ice field (PCA 82502), suggesting they may be paired as part of the same fall (Warren et al, 2009). The spherical shape of these vesicles implies that they formed by exsolution of volatiles from a melt (McCoy et al, 2002), which was later modeled as a mixed CO-CO_2 gas (McCoy et al, 2006). These gases would have nucleated as bubbles at depth that were preserved in relatively small (≤0.5 m) magma dikes (McCoy et al, 2006). An alternative theory suggests that PCA 91007 formed as an impact melt (Warren et al, 2009); the vesicles could form from exsolution of S_2 in melt dikes beneath the crater floor (T.J. McCoy, pers. comm.; Benedix et al, 2008). These theories are discussed further in the section on petrogenesis below.

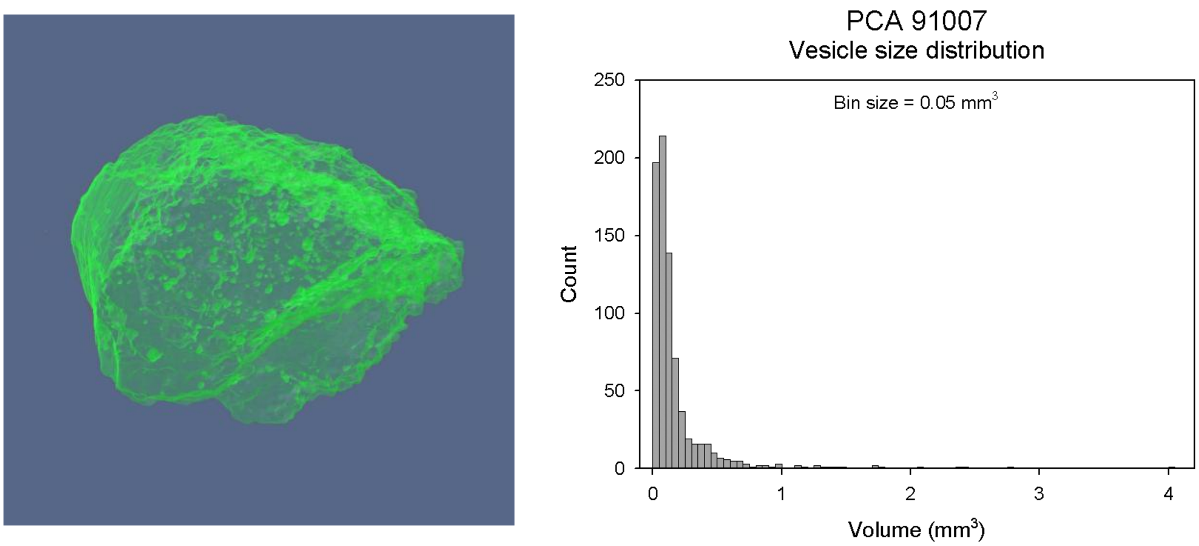

Figure 4*: 3d visualization and volume distribution of vesicles from PCA 91007. From McCoy et al (2006), supplemental materials section, which also includes Quicktime videos of CT slice data and 3d visualizations: http://www.ctlab.geo.utexas.edu/pubs/McCoy_KWBWD/mccoy_kwbwd.htm.*

Mineral Chemistry:
Pyroxene: Pyroxene compositions range continuously from Wo_5Fs_{56} to $Wo_{30}Fs_{35}$, with little variation in enstatite content (Antarctic Meteorite Newsletter 15/2; Burbine et al, 2001). Pyroxenes are generally equilibrated, with ≤1 µm exsolution lamellae; they have been classified as Type 4 clasts on the Takeda and Graham (1991) scale, showing clouding and increases in Ca content from Ca-poor cores to Ca-rich rims (Yamaguchi et al, 1996; Warren et al, 1996b, 1996c). This indicates only moderate metamorphism (Warren et al, 1996b, 1996c). PCA 82502, the proposed pair of PCA 91007, has almost congruent pyroxene compositions (Burbine et al, 2001).
Plagioclase: PCA 91007 has variable plagioclase compositions, from $An_{80\text{-}91}$ (Antarctic Meteorite Newsletter 15/2). No other compositional data on PCA 91007 plagioclase is available.

Whole-Rock Chemistry: A summary of whole-rock PCA 91007 major element analyses is shown in **Table 1**, with minor and trace elements in **Table 2**. PCA 91007 has a whole-rock Mg# of 37, and plots with the main group/Nuevo Laredo eucrite trend; there is no significant depletion of alkalis or incompatible elements relative to "normal" eucrites, unlike the sub-eucrite levels in Ibitira (Warren et al, 1996b, 1996c; Scott et al, 2009). PCA 91007,10 shows Ce/Ce* ratios that are lower than expected values, coupled with a high Eu/Sm ratio, both of which may be attributed to weathering alteration (Mittlefehldt and Lindstrom, 2003). REEs from two different PCA 91007 samples (,4 and ,10) are shown relative to CI in **Figure 5**; the results from PCA91007,10 (Mittlefehldt and Lindstrom, 2003) are significantly different than those from PCA91007,4 (Warren et al, 1996b; 2009). This may reflect the aforementioned weathering alteration in sample PCA91007,10, but I have included the data nonetheless for comparison purposes.

Most notably, PCA 91007 has a “barely detectable but significant” enrichment in siderophile elements over normal eucrites, especially Ni, Os, and Ir, approaching levels seen in polymict eucrites (Warren et al, 1999; Warren et al, 2009; Scott et al, 2009). This could be from the assimilation of small amounts of chondritic material into a melt, though these levels would be much higher if chondritic contamination was also responsible for the positive oxygen anomalies seen in PCA 91007 (Warren et al, 2009; Scott et al, 2009; see below). Warren et al (2009) classified PCA 91007 as an impact-melt polymict eucrite based primarily on these siderophile element abundances (coupled with the occurrence of vesicles).

It is also worth noting that PCA 82502 has very similar major, minor, and trace element abundances to PCA 91007 (Burbine et al, 2001; Warren et al, 2009).

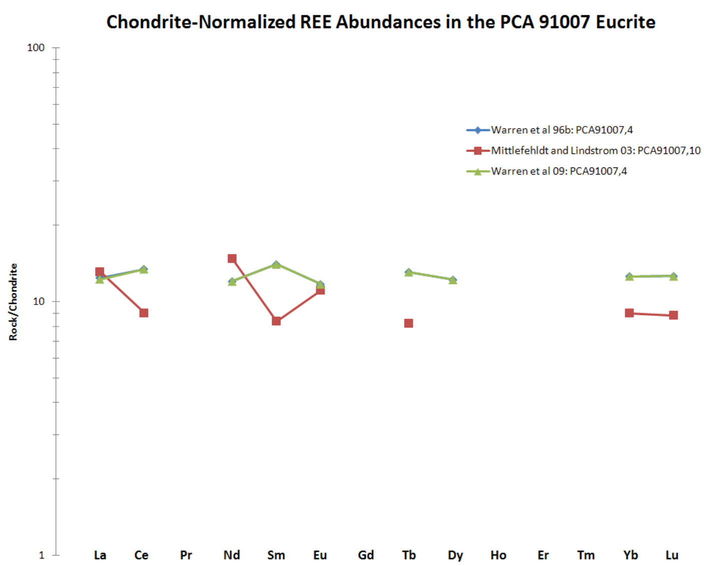

Figure 4*: Chondrite-normalized REE abundances in PCA 91007. Interpretation is limited by the paucity of data, as well as heterogeneities between different samples, but the pattern appears to show relative flat enrichment (10xCI). Data from Warren et al (1996b) is very similar to data on the same section from Warren et al (2009), and thus the points are nearly superimposed. The reference CI chondrite is from Evensen et al (1978).*

Table 1: Major element analyses of PCA 91007.

reference	**Warren et al 96b**	**Burbine et al 01**	**Mittlefehldt and Lindstrom 03**	**Warren et al 09**
comments	PCA91007,4	--	PCA91007,10	PCA91007,4
weight	328 mg	--	75.68mg	328 mg
SiO_2	49.85	--	--	49.92
TiO_2	0.73	--	--	0.73
Al_2O_3	13.04	--	--	13.00
FeO	18.14	18.7	18.80	18.16
MnO	0.53	--	--	0.53
MgO	5.97	--	--	6.00
CaO	10.36	10.2	9.9	10.34
Na_2O	0.44	0.49	0.48	0.46
K_2O	0.04	0.06	0.06	0.04
Cr_2O_3	0.30	--	0.32	0.30
Mg#	**37**	**--**	**--**	**37**
technique:	*INAA/RNAA/EPMA*	*INAA*	*INAA*	*INAA*

Table 2: Minor and trace element analyses of PCA 91007.

reference	**Warren et al 96b**	**Warren et al 99**	**Mittlefehldt and Lindstrom 03**	**Warren et al 09**
weight	328 mg	291 mg	75.68 mg	328 mg
comments	PCA91007,4	PCA91007,4	PCA91007,10	PCA91007,4
Sc ppm	30.6	--	--	30.6
V ppm	68	--	--	68
Co ppm	6	--	5.67	6
Ni ppm	<19	7.5	--	7.5
Cu ppm	--	--	--	--
Zn ppm	25	--	--	3.5
Ga ppm	1.31	--	--	1.3
Ge ppm	--	6.2	--	6.2
Sr ppm	94	--	89	94
Zr ppm	69	--	88	69
Ba ppm	<33	--	37	<33
La ppm	3.04	--	3.21	3
Ce ppm	8.6	--	5.78	8.6
Nd ppm	5.7	--	7	5.7
Sm ppm	2.16	--	1.29	2.16
Eu ppm	0.68	--	0.643	0.68
Tb ppm	0.49	--	0.308	0.49
Dy ppm	3.1	--	--	3.1
Yb ppm	2.08	--	1.49	2.08
Lu ppm	0.32	--	0.224	0.32
Hf ppb	1440	--	1570	1440
Ta ppb	174	--	193	174
Re ppb	--	0.020	--	0.02
Os ppb	--	0.29	--	0.290
Ir ppb	<2.8	0.26	--	260
Pt ppb	--	--	--	--
Au ppb	<0.38	0.072	--	0.072
Th ppb	380	--	240	380
U ppb	<150	--	--	103
Br ppm	--	--	--	0.23
technique:	*INAA/RNAA/EPMA*	*RNAA*	*INAA*	*INAA/RNAA*

Radiogenic Isotopes: An Ar-Ar age was reported for PCA 91007 by Bogard and Garrison (2001, 2003); the age release spectrum suggested terrestrial K and Ar adsorption, ^{40}Ar diffusive loss, and ^{39}Ar recoil distribution, but three extractions over 27-49% of the ^{39}Ar release show a concordant age of ~4.444 Ga, which was taken as the lower limit of K-Ar isotopic closure (**Figure 6**). The total Ar-Ar age of 4.08 Ga indicates that PCA 91007 was not significantly reset by late bombardment (Bogard and Garrison, 2003). PCA 82502, the proposed pair, shows a similar Ar release spectrum, with a more precisely defined age of 4.506 ± 0.009 Ga, and its total Ar-Ar age (4.41 Ga) also suggests that it also escaped later resetting (Bogard and Garrison, 2003).

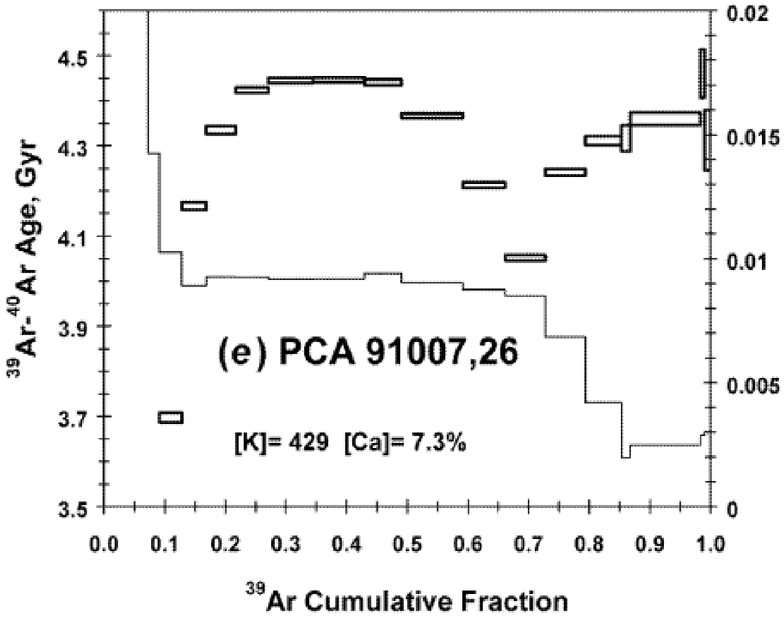

***Figure 6**: Ar-Ar age release spectrum from PCA 91007 (sample ,26). The central plateau, comprising 27-49% of the spectrum, gives an apparent age of 4.444 Ga. From Bogard and Garrison (2003).*

Cosmogenic Isotopes: Cosmogenic ^{21}Ne (36.9 x 10^{-9} cm^3 STP/g) and ^{38}Ar (18.9 x 10^{-9} cm^3 STP/g) were reported for PCA 91007 by Miura et al (1994), with a reported ^{38}Ar cosmic-ray exposure age of 13 Ma.

Other Isotopes: Oxygen isotopes were recently analyzed in PCA 91007 by Scott et al (2009), with reported values that are significantly different than most HEDs ($\delta^{18}O$ = 3.701‰ ± 0.116‰, $\delta^{17}O$ = 1.738‰ ± 0.062‰, and $\Delta^{17}O$ = -0.202‰ ± 0.011‰). Like Pasamonte, a well-studied eucrite with similarly high siderophile element abundances, $\Delta^{17}O$ values for PCA 91007 plot +5σ from the eucrite fractionation line (Scott et al, 2009; **Figure 7**). It is important to note that chondritic contamination may provide an explanation for the oxygen isotope compositions in both Pasamonte and PCA 91007, but Scott et al (2009) do not support this possibility, given that siderophile element abundances would be significantly higher if enough contamination occurred to significantly shift $\Delta^{17}O$ values; thus, a parent body other than Vesta has been proposed for both eucrites. Finally, leaching experiments were engaged to determine whether this anomalous oxygen isotope composition was an artifact of terrestrial weathering, but the differences between HCl-leached and untreated samples were determined to be insignificant (Scott et al, 2009).

No oxygen isotope analyses are available for PCA 82502.

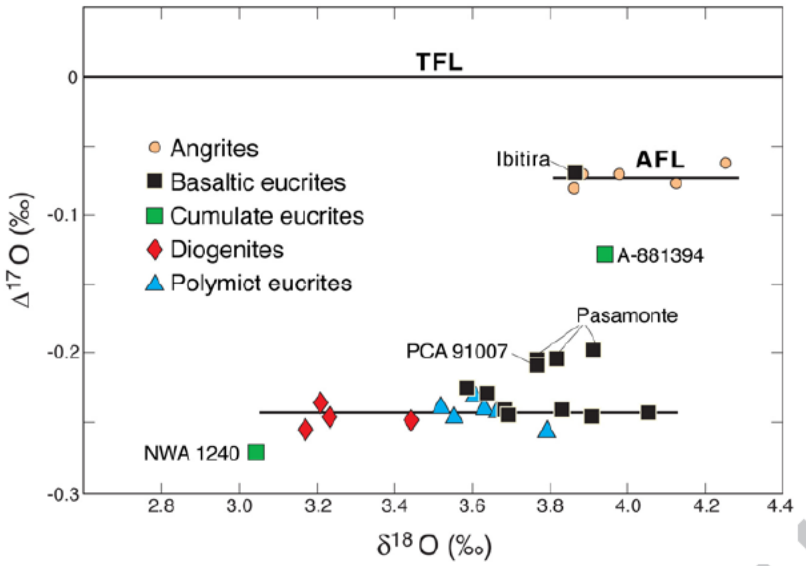

Figure 7: *$\Delta^{17}O$ plotted against $\delta^{18}O$ for a subset of the basaltic achondrites. TFL = terrestrial fractionation line, AFL = angrite fractionation line (which, notably, includes Ibitira), and the bottom solid line represents the eucrite fractionation line (EFL). Both PCA 91007 and Pasamonte plot 5σ above the EFL; coupled with other lines of evidence (see text), this most likely indicates a parent body other than the one for main-group eucrites, diogenites, polymict eucrites, and howardites. From Scott et al (2009).*

(A small note: though Scott et al, 2009 have shown only two cumulate eucrites that plot significantly off the EFL, there are many other cumulate eucrites that do plot on the EFL.)

Experiments: Thermoluminescence intensity has been reported for PCA 91007 as 5±1 krad at 250°C, which is concordant with the value for PCA 82502, 6±1 krad at 250°C (measured by Sears and coworkers, published in Grossman, 1994). Values for the bulk reflectance spectrum of PCA 91007, PCA 82501, and PCA 82502 are also very similar (Burbine et al, 2001).

Metamorphism: PCA 91007 was originally noted to be "only moderately metamorphosed" (Warren et al, 1996b, 1996c); pyroxenes exhibit sub-micron to 1 micron-sized exsolution lamellae, and their compositions are generally equilibrated, with clouding and Ca-enrichment from core to rim, and are thus classified as Type 4 clasts on the Takeda and Graham (1991) scale (Yamaguchi et al, 1996).

Shock Effects: PCA 91007 is generally unbrecciated (Warren et al, 1996b, 1996c), and though many authors have referred to the "limited textural evidence" that PCA 91007 is brecciated (e.g., Warren et al, 2009), this evidence has never been explicitly described in the literature.

Petrogenesis: Warren et al (1996b, 1996c) made the initial contention that PCA 91007 represented a quenched melt, primarily based on the pervasive fine-grained nature of the meteorite. Warren et al (2009) has recently followed up on this argument by asserting that PCA 91007 and PCA 82502 are impact melts, based not only on the fine-grained, generally unbrecciated character of both eucrites, but on other vesicular eucrites interpreted to be impact melts (e.g., NWA 1240 and Y-981651: see Barrat et al, 2003 and Warren et al, 2009), and significantly enriched siderophile element abundances in PCA 91007 and PCA 82502 that are not seen in other vesicular eucrites (including NWA 1240 and Y-981651) (Warren et al, 2009). It is worth noting that NWA 1240 and Y-981651 are also different from PCA 91007 and PCA 82502 in terms of their vesicular character: whereas PCA 91007 and PCA 82502 have a ~0.5 vol% of very small (<0.3 mm diameter) vesicles, both NWA 1240 and Y-981651 contain larger, 2-3 mm vesicles (Barrat et al, 2003; Warren, 2003; McCoy et al, 2006; Warren et al, 2009). Thus, in asserting an impact-melt origin for PCA 91007 and PCA 82502, Warren et al (2009) cautions that this classification is made with "admittedly… an unusual degree of uncertainty."

High-resolution X-ray Computed Tomography (CT) work from McCoy et al (2006), coupled with vesicle growth modeling, revealed a significantly different possible origin for PCA 91007. They posited that the vesicles were formed by deep (20-30 km) exsolution of a mixed CO-CO_2 gas, most likely within a small (<50 cm) dike that quenched in the cold outer shell (~5 km) of the parent body. In addition, the authors directly address the impact melt origin favored by Warren et al (2009) by arguing that "formation of vesicular basalts as impact melts… requires an unreasonably thick melt sheet" to prevent magma fragmentation and gas escape (McCoy et al, 2006).

How can we reconcile these two seemingly contradictory hypotheses for the formation of PCA 91007? Clues can be found in a recent investigation of vesicular impact-melt L-chondrite PAT 91501 (T.J. McCoy, pers. comm.), in which vesicles most likely formed during impact by sulfur vaporization in melt dikes beneath the crater floor (Benedix et al, 2008). This environment allows for rapid cooling and at the same time resolves the problem of overburden pressure needed to prevent melt fragmentation (T.J. McCoy, pers. comm.), but unlike in PCA 91007, there is clear evidence of sulfur vaporization preserved in metal-sulfide intergrowths within PAT 91501 vesicles (Benedix et al, 2008). Also, PAT 91501 contains much larger vesicles (≤1.4 cm) in greater abundances (~2 vol%) than PCA 91007 (Benedix et al, 2008), and thus I would argue that its vesicular character is more similar to NWA 1240 (Barrat et al, 2003) and Y-981651 (Warren et al, 2009) than PCA 91007. Still, the work of Benedix et al (2008) provides a reasonable analog for the formation of PCA 91007 by quenching from an impact melt within the confines of a small dike, and future work will likely clarify this problem further.

Pairing: There are numerous mentions of PCA 82502 throughout this paper, and though PCA 91007 and PCA 82502 are not officially paired, this classification is highly warranted, given the number of similarities between them (especially regarding vesicles, which are extremely rare in eucrites). Pairing is supported by the work of Warren et al (2009), as nearly the same contention is made. Some of the work done solely on PCA 82502 is omitted from this paper, given that the focus here is on PCA 91007, but so far, no truly incompatible results have been found that would disqualify the pairing. The ~0.9 kg PCA 82502 sample was initially paired with a much smaller but very similar sample, the ~50 g unbrecciated eucrite PCA 82501 (Antarctic Meteorite Newsletter 6/2); as little (if any) work has been published on PCA 82501, it may be worth investigating as a pair to the other two larger samples.

Processing: Many different samples have been divided from the original mass of PCA 91007; a summary of their history is contained in **Table 3**, below.

Table 3: Processing and allocation history of PCA 91007, courtesy of C. Satterwhite at JSC. This data is current as of 08/11/2009.

Sample #	Parent	Location/Investigator	Mass (g)	Description
PCA 91007, 0	0	NMNH (Smithsonian)	103.940	Documented Piece
PCA 91007, 1	0	NMNH (Smithsonian)	66.620	Documented Piece
PCA 91007, 2	0	NMNH (Smithsonian)	13.677	Chips + FI
PCA 91007, 3	0	Entirely Subdivided	--	Potted Butt
PCA 91007, 4	0	Warren, P.H.	0.340	Interior Chip
PCA 91007, 5	0	Sears, D.W.G. (NSF)	0.330	TL Chip/IP
PCA 91007, 7	3	MCC (Houston)	0.010	Thin Section
PCA 91007, 8	3	Mason, B.H. (NSF)	0.010	Thin Section
PCA 91007, 9	1	Lipschutz, M.E.	0.580	Interior Chip
PCA 91007, 10	1	Mittlefehldt, D.	0.590	Interior Chip
PCA 91007, 11	1	Sugiura, N.	2.160	Interior Chip
PCA 91007, 12	1	MCC (Houston)	1.170	Potted Butt
PCA 91007, 13	1	NMNH (Smithsonian)	23.500	Exterior Chips + FI
PCA 91007, 14	1	NMNH (Smithsonian)	5.950	Interior Chips
PCA 91007, 16	3	Delaney, J.S.	0.010	Thin Section
PCA 91007, 17	12	MCC (Houston)	0.010	Thin Section
PCA 91007, 18	12	Scott, E.	0.010	Thin Section
PCA 91007, 19	3	MCC (Houston)	0.010	Thin Section
PCA 91007, 20	3	MCC (Houston)	0.010	Thin Section
PCA 91007, 24	3	MCC (Houston)	0.010	Thin Section
PCA 91007, 26	14	Bogard, D.	0.340	Interior Chips
PCA 91007, 27	2	Binzel, R.P.	0.435	Interior Chip
PCA 91007, 29	2	Hiroi, T.	0.062	Interior Chip