PRIMORDIAL ICE ABUNDANCE IN CV CHONDRITES. D. S. Ebel[1], M. K. Weisberg[2,1], J. M. Friedrich[3,1], [1]American Museum of Natural History, Central Park West at 79th St., New York, NY 10024 (debel@amnh.org), [2]Kingsborough College, CUNY, Brooklyn, NY 11235, [3]Dept. Chemistry, Fordham University, Bronx, NY 10458.

Introduction: The CV carbonaceous chondrites are subdivided into two subgroups, oxidized (CV_{Ox}) and reduced (CV_R) based on modal metal/magnetite ratios and the Ni content of opaque minerals [1]. The oxidized CV's are further subdivided into CV_{OxA} and CV_{OxB} subgroups [2]. Here, we compare two Allende (CV_{OxA}) and Mokoia (CV_{OxB}) with two CV_R (Vigarano and Nova002).

The matrix of CV chondrites hosts interstellar grains and macromolecular carbon, and is dominated by FeO-rich olivine [e.g., 3, 4]. Aqueous alteration of matrix occurred on chondrite parent bodies due to the effects of water, perhaps originally accreted as ice particles [5, 6]. Here, we focus on what is missing from matrix, by correlating porosity and matrix abundance to the degree of oxidative alteration of CV chondrites. We show that primordial ice is likely to be another original component of matrix in CV chondrites.

Methods: Polished thin and thick sections of chondrites were mapped at from 4 to 9 μm/pixel resolution for the x-ray intensities of nine major elements using WDS and EDS spectrometers on the Cameca SX100 electron microprobe at AMNH. Hand-drawn inclusion outlines are the basis for detailed, pixel-by-pixel image analysis. Methods now includes bulk chemical analysis of each individual inclusion and of matrix [7-10]. We infer volume % of chondrite components directly from area % measurements [11, 12]. We have reported the abundance of matrix in CV_{Ox} Allende [13, 14] and the abundance of inclusions across a range of CV chondrites [15]. Since then, [16] have published comprehensive data on meteorite porosities measured using He pycnometry.

We have set aside data from Leoville (CV_R), because Leoville is heavily weathered. Porosity has not been reported for Tibooburra and Bali (CV_{OxB}). Its chemistry and matrix/inclusion ratio strongly indicates that Nova002 is a member of the reduced subclass. Although it is a find, Nova002 is only slightly weathered [17].

The vast majority of porosity in these CV meteorites is in the matrix. Although it has been demonstrated that chondrules and CAIs in Allende contain void space [cf. 18, 19], we assume here that the porosity in inclusions is equivalent between, and negligible overall, among the four CV chondrites studied here.

Results: In Table 1 we report CV subclass, origin, and type, as determined by [20] and [21]. We report porosity (volume %) from [16] and the differences between mean CV_{Ox} and CV_R values. Matrix abundances (volume %) are our results, including small isolated olivine grains and metal/sulfide grains with matrix. The final column reports matrix abundance (including lithic fragments and metal/sulfide) reported by [1] and for Nova002 by [17].

It is immediately clear from the differences in matrix abundance and porosity (Ox - R in Table 1) that the matrix grain abundance (matrix - porosity) in all these CV chondrites is about the same, 30.8 ± 3.1 (Table 2). Renormalization of each of the four CV chondrites to zero porosity results in a mean matrix abundance of 37.0 ± 5.6 volume%, and a mean matrix/inclusion ratio of 0.60 ± 0.15 (Table 2). In Table 2, pore vol% is subtracted from matrix vol% (mat-pores), and vol% "inclusions" includes all chondrules, Ca-, Al-rich inclusions, and amoeboid olivine aggregates, the complements to the matrix component.

Table 1: Data for CV chondrites. Matrix abundance is from this work. Porosity is from [16]. (* from [1], [17]).

	subclass	fall/find	type[20]	type[21]	porosity	matrix	earlier*
Allende	oxA	fall-1969	3.2	>3.6	21.9	56.7	44.4
Mokoia	oxB	fall-1908	3.2	~3.6	27.7	55.1	46.9
Nova002	*n.d.*	find	*n.d.*	*n.d.*	6	36.4	33.9
Vigarano	red	fall-1910	3.3	3.1-3.4	8.3	38.8	39.6
avg CV_{Ox}					24.8	55.9	45.7
avg CV_R					7.2	37.6	36.8
Ox - R					17.7	18.3	8.9

Table 2: Recalculated data (vol%).

			*Renormalized to zero porosity		
	mat - pores	inclusions	matrix*	inclusions*	mat/incl.*
Allende	34.8	43.3	44.60	55.40	0.805
Mokoia	27.4	44.9	37.86	62.14	0.609
Nova002	30.4	63.6	32.30	67.70	0.477
Vigarano	30.5	61.2	33.22	66.78	0.498
mean	30.8	53.3	37.0	63.0	0.60
std. dev.	3.1	10.7	5.6	5.6	0.15

Discussion: These results explain the apparent difference in matrix abundance between the oxidized and reduced subclasses of CV chondrites as due to porosity. However, the mean matrix abundance remains 8.5% higher in CV_{Ox} than in CV_R, and highest in Allende (CV_{OxA}). In this calculation, we have not accounted for increases in matrix grain size due to formation of secondary minerals (e.g., the molar volume of fayalite is 4% larger than that of forsterite [22, 23] during aqueous alteration. Matrix grains are coarser in CV_{Ox} Allende than in CV_R Vigarano [24]. Because the exact primary mineralogy of CV chondrite matrix is

uncertain [3, p.220], and quantitative assessment of the effects of aqueous alteration is difficult, we are not able to calculate the effect of alteration on matrix grain size.

What previously occupied the excess 18 volume% pore space measured in the oxidized CV relative to the reduced CV chondrites? Previous observations [e.g., 5] strongly suggest that the matrix in the oxidized CV contained water ice grains as a primary accreted component. Carbonates are not reported in CV chondrite matrix [3], but calcite and dolomite are found in CM chondrite matrix [3, 5, 25].

We have also measured the matrix abundance in a suite of CO chondrites and the ungrouped C2 chondrite Acfer 094. Table 3 lists these, types determined by [26], and porosity [16]. These results show no apparent correlation between porosity and petrologic grade. This result is consistent with previous work that found CO chondrites to be thermally altered, with minimal aqueous alteration, in contrast to the CV chondrites [27].

Table 3: Data for CO chondrites and Acfer094.

	fall/find	type [26]	porosity	matrix	mat - por
Colony	find	3.0	9.2	38.1	28.9
Kainsaz	fall-1937	3.2	9.3	45.1	35.8
Ornans	fall-1868	3.4	34.2	51.7	17.5
Lancé	fall-1872	3.5	9.2	48.4	39.2
Warrenton	fall-1877	3.7	24	35.4	11.4
Acfer094	find	C2-ung	*n.d.*	56.5	

Implications: The data in Table 1 indicate that small ice grains accounted for up to 44% of the matrix volume in CV_{Ox} and only up to ~19% of the matrix volume in CV_R. That's a lot of ice! However, these percentages are upper bounds because they do not allow for porosity intrinsic to the accretion process.

Water ice sublimes at ~240K and CO_2 ice at ~140K at 10^{-3} bar total pressure. The vapor pressure during chondrite accretion was likely much lower than this. Our data add evidence that the sublimation temperatures of water and CO_2 ice place upper and lower bounds on the accretion temperatures of the CV chondrites. If CV chondrites represent the precursors of planets, then their original ice content would affect the volatile budgets of emerging worlds.

Matrix is the most heterogeneous component of chondritic meteorites. Evidence for five different components of chondrite matrix was described by [4, p.725]: 1) average dust from the sun's parent molecular cloud, 2) material that evaporated from inclusions and recondensed onto matrix, 3) inclusion fragments, and locally evaporated molecular cloud material, either 4) fully or 5) partially recondensed as or on fine grained dust.

Here we have presented circumstantial evidence that strongly suggests a sixth primordial component of matrix, at least in CV chondrites: primordial water ice.

Acknowledgments: AMNH student interns S. McKnight, J. Finkelstein and G. Lutzky assisted in this work. The AMNH Physical Sciences REU Program (NSF #AST-055258) supported H. Rodriguez (2006), C. E. Brunner (2007), K. Leftwich (2008), and K. Konrad (2009). The AMNH HSSRP program supported M. Lu and I. Erb (2008-9). Research was supported by U.S. N.A.S.A. grants NANG06GD89G and NNX10AI42G (DSE), and NNX12AI06G (MKW). This research has made use of NASA's Astrophysics Data System Bibliographic Services.

References: [1] McSween H. Y. Jr. (1977) *Geochim. Cosmochim. Acta, 41*, 1777-1790. [2] Weisberg M. K. et al. (1997) *Meteoritics & Planet. Sci., 32*, A138-139. [3] Brearley A. and Jones R. (1998) In *Planetary Materials* (J. J. Papike, ed.), pp 3-1 - 3-95. *Rev. in Mineralogy, 36*. [4] Huss G. R. et al. (2005) In *Chondrites and the Protoplanetary Disk*, eds. Krot A. et al., Astronomical Soc. of the Pacific Conf. Ser. 341, 701-731. [5] Bunch T. E. and Chang S. (1980) *Geochim. Cosmochim. Acta, 44*, 1543-1577. [6] Grimm R. E. and McSween H. Y. Jr. (1989) *Icarus, 82*, 244 - 280. [7] Ebel D. S. et al. (2014) *LPS XLV*, Abstract #1206. [8] Crapster-Pregont E. J. et al. (2014) *LPS XLV*, Abstract #1379. [9] Lobo A. et al. (2014) *LPS XLV*, Abstract #1423. [10] Bayron J. M. et al. (2014) *LPS XLV*, Abstract #1225. [11] Chayes F. (1956) *Petrographic Modal Analysis*, Wiley (113p). [12] Dodd R. T. (1976) *Earth Planet. Sci. Letters, 30*, 281-291. [13] Brunner C. E., Ebel D. S., Weisberg M. K. (2008) *Meteoritics Planet. Sci., 43*, A28. [14] Ebel D. S., Brunner C. E., Weisberg M. K. (2008) *LPS XXXIX*, Abstract #2121. [15] Ebel D. S. et al. (2009) *LPS XL*, Abstract #2065. [16] Macke R. J., Consolmagno G. J., Britt D. T. (2011) *Meteoritics Planet. Sci., 46*, 1842-1864. [17] Treiman A. H. and DeHart J. M. (1992) *Meteoritics, 27*, 299. [18] Murray J. et al. (2003) *LPS XXXIV*, Abstract #1999. [19] Ebel D.S. and Rivers M. L. (2007) *Meteoritics Planet. Sci., 42*, 1627-1646. [20] Guimon R. K. et al. (1995) *Meteoritics, 30*, 704-714. [21] Bonal L. et al. (2006) *Geochim. Cosmochim. Acta, 70*, 1849-1863. [22] Yoder H. S. Jr. and Sahama Th. G. (1957) *Am. Mineral., 42*, 475-491. [23] Fujii (1960) *Am. Mineral., 45*, 370-382. [25] Krot A. N., Scott E. R. D., Zolensky M. E. (1995) *Meteoritics Planet. Sci., 30*, 748-775. [25] Johnson C. A. and Prinz M. (1993) *Geochim. Cosmochim. Acta, 57*, 2843-2852. [26] Grossman J. N. and Brearley A. J. (2005) *Meteoritics Planet. Sci., 40*, 87-122. [27] Zolensky M. et al. (1993) *Geochim. Cosmochim. Acta, 57*, 3123-3148.