Carbon in Meteorites

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V · T · E

Goldschmidt classification in the periodic table

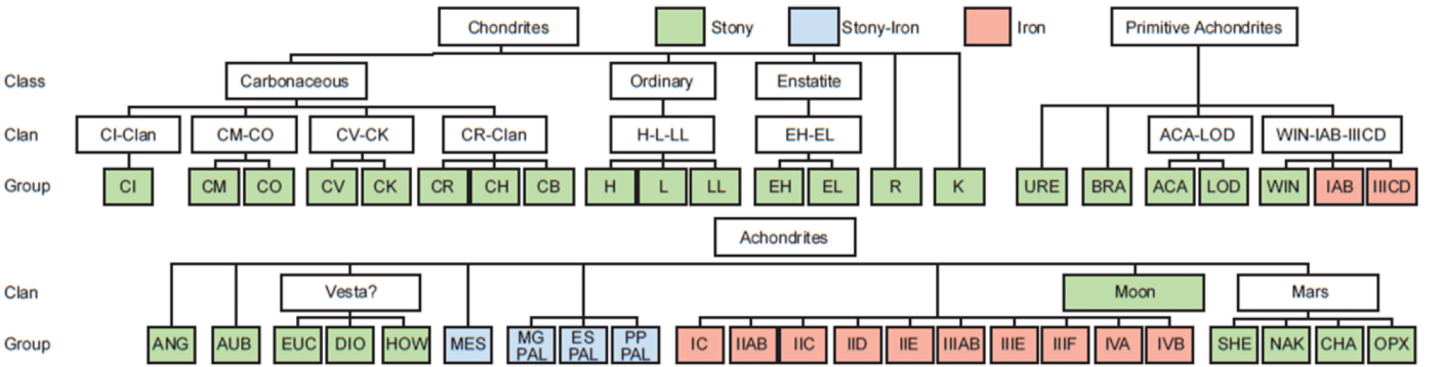
Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	(104) Rf	(105) Db	(106) Sg	(107) Bh	(108) Hs	(109) Mt	(110) Ds	(111) Rg	(112) Cn	(113) Uut	(114) Fl	(115) Uup	(116) Lv	(117) Uus	(118) Uuo
* Lanthanides			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
** Actinides			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	(95) Am	(96) Cm	(97) Bk	(98) Cf	(99) Es	(100) Fm	(101) Md	(102) No	(103) Lr	

Legend

Lithophile | Siderophile | Chalcophile | Atmophile | very rare

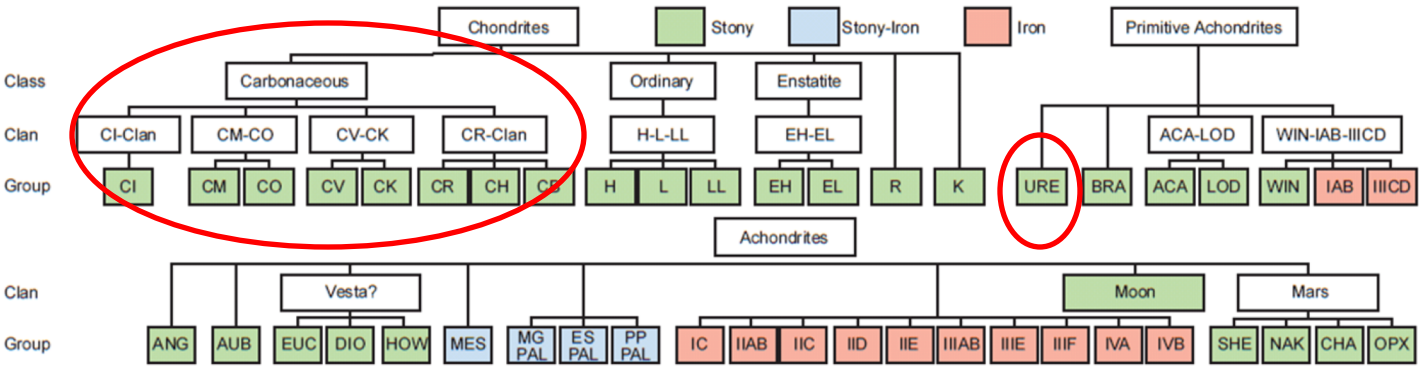
- **<u>Lithophile</u> (rock loving) elements remain on or close to the surface because they combine readily with oxygen, forming compounds that do not sink into the core.**
- **<u>Siderophile</u> (iron loving) elements are the high-density transition metals which tend to sink into the core because they dissolve readily in iron.**
- **<u>Chalcophile</u> (ore loving) elements that combine readily with sulfur and/or some other chalcogen other than oxygen.**
- **<u>Atmophile</u> (atmosphere loving) elements are either gases or form volatile hydrides.**

Meteorite Groups

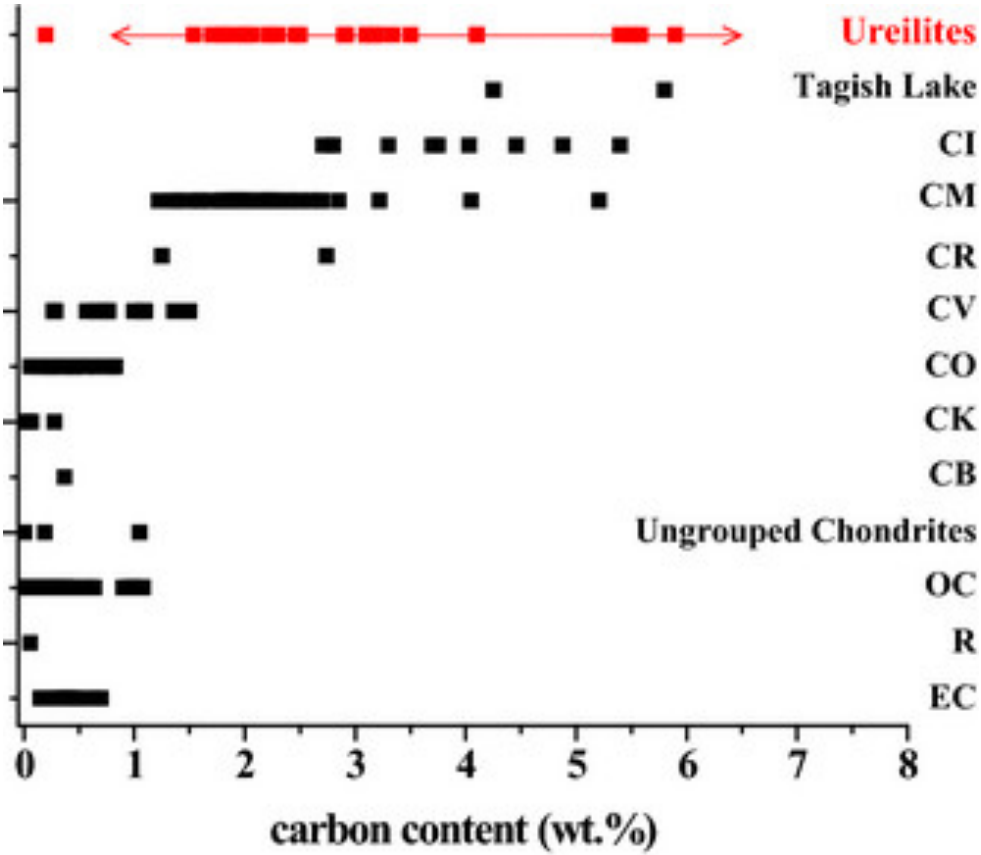


≈ 46 Groups…..

But not many have significant carbon



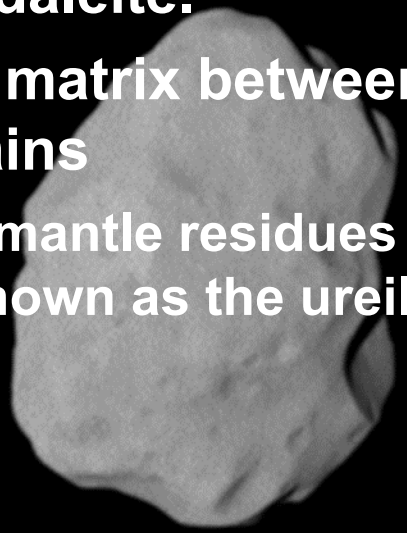
Carbon in Meteorites



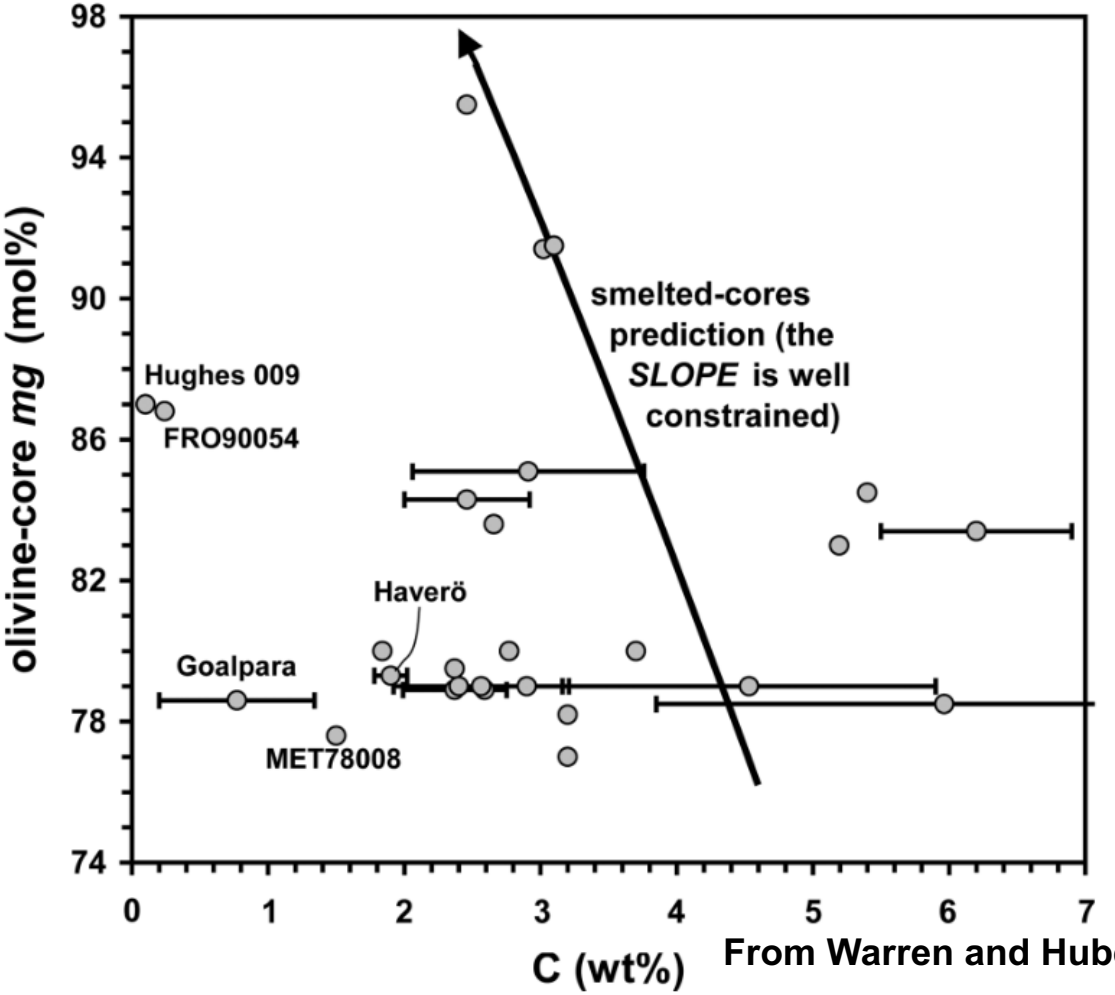
From Goodrich et al., 2014

Carbon in Ureilites

- Oddly, the most carbon-rich meteorites are Ureilites
- They are carbonaceous olivine-pyroxene achondrites. Contain up to 7 wt.% carbon as graphite, diamond, and lonsdaleite.
- The carbon is entirely in the matrix between the olivine and pyroxene grains
- They are believed to represent mantle residues from a single planetary body known as the ureilite parent body.

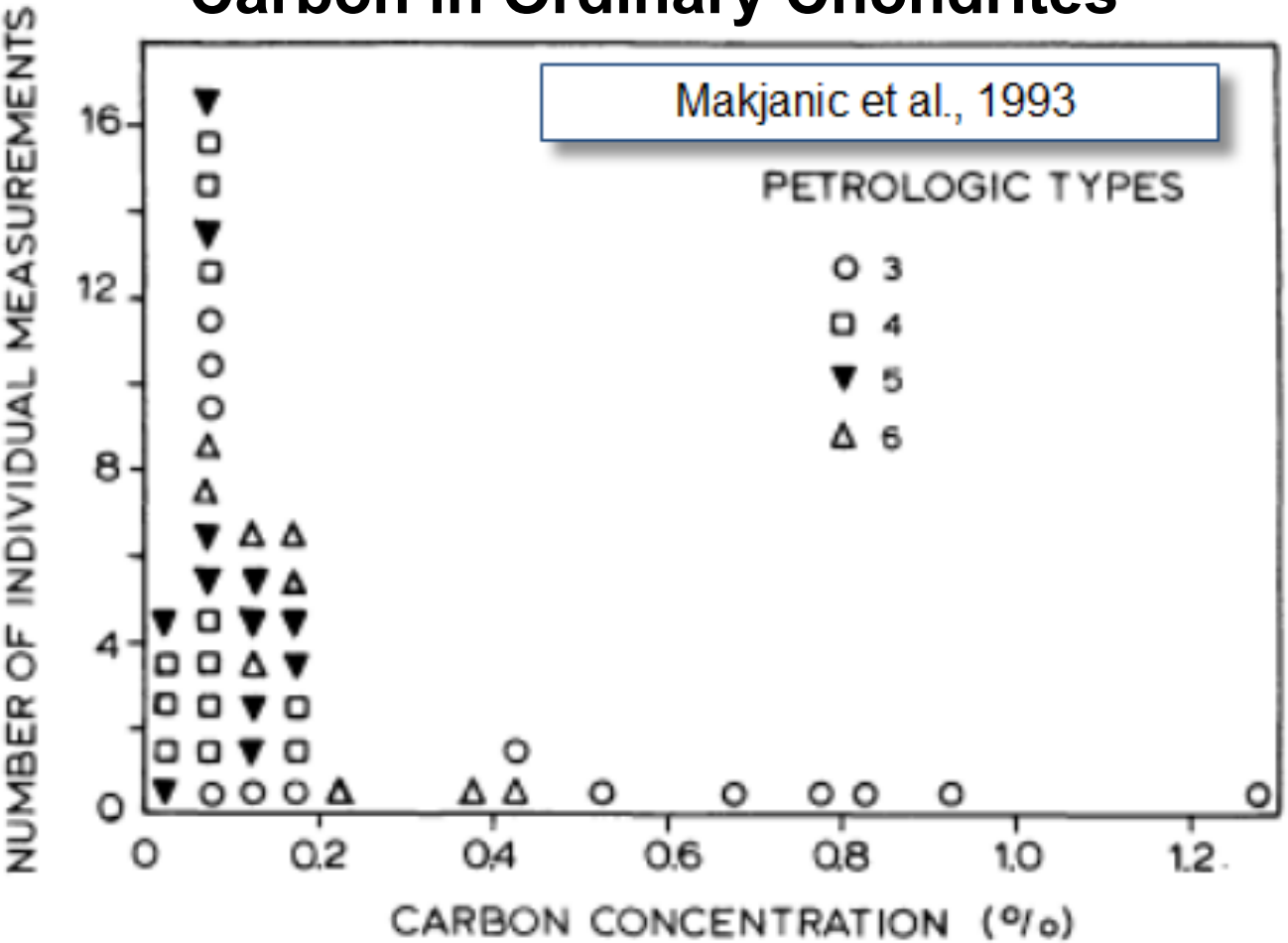


Carbon in Ureilites



From Warren and Huber, 2006

Carbon in Ordinary Chondrites

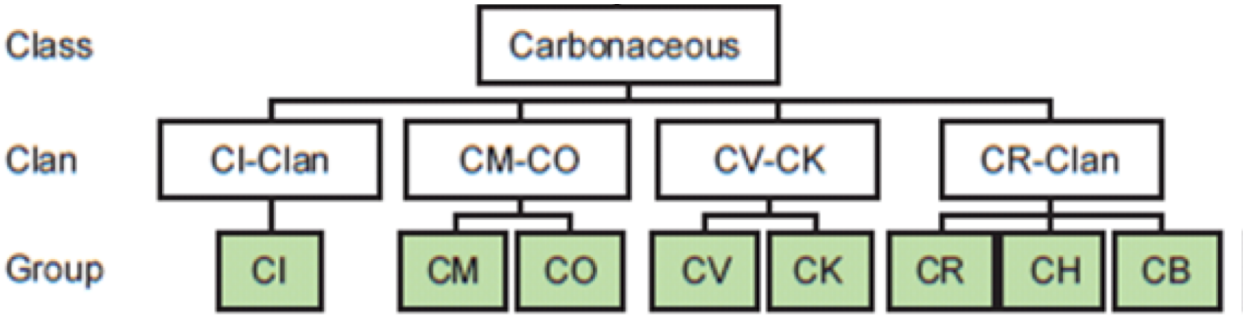


Carbon in Iron Meteorites

Group	structure*	Ni wt%	Ga µg/g	Ge µg/g	Ir µg/g	C µg/g	P mg/g	S wt%	Cr µg/g	Co mg/g	Cu µg/g	Mo µg/g	W µg/g	Pd µg/g	Au µg/g	As µg/g	Sb ng/g	Group
IAB	see note 1	6.4	96	400	2.7	-	2.1	-	16	4.6	132	8.2	1.6	3.5	1.5	11	270	IAB
IC	var.	7.1	51.7	230	0.38	-	4.3	-	70	4.6	160	7.7	1.3	3.5	1.14	11	98	IC
IIAB	H (IIA)	6.15	58.3	173	10	2000[a]	6	0.20[a]	38	5.3	129	6.9	2.1	2.6	1.1	9.9	201	IIAB
	Ogg (IIB)	6.1[a]	-	64[b]	11a	-	20[a]	17.0[b]	-	-	-	-	-	-	1.0[a]	-	-	IIAB
		5.1[b]	-	-	1.3b	-	10[b]	-	-	-	-	-	-	-	-	-	-	IIAB
IIC	Opl	10.8	37.3	94.6	6.4	-	5.3	-	87	6.5	260	8.4	-	6	1.1	8.2	150	IIC
IID	Om	11.2	76.2	87	9.9	-	9.8	-	31	4.7	280	9.4	2.4	5.3	1.1	10	220	IID
IIE	anom.	9.13	24.4	68.3	4.1	-	-	-	-	4.7	416	6.8	0.78	5.3	1.6	16	300	IIE
IIF	var.	12.9	9.8	140	6.2	-	2.6	-	-	7.0	300	-	1	-	1.5	16	250	IIF
IIIAB	Om	8.49	19.7	38.9	4.1	140[a]	5.6	1.4[a,d]	40	5.0	160	7.2	1	3.5	1.2	10.5	265	IIIAB
		8.25[a]	18.5[c]	40[a]	5.0[a]	-	9.3[a]	5.0[b]	-	-	160	-	-	-	1.1[a]	-	-	IIIAB
		7.6[b]	-	35[b]	3.5[c]	-	-	6.0[c]	-	-	160	-	-	-	0.7[b]	-	-	IIIAB
		8.2[c]	-	36.25[c]	-	-	-	-	-	-	160	-	-	-	1.05[c]	-	-	IIIAB
IIICD	see note 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	IIICD
IIIE	Og	8.49	17.6	35.6	4.1	-	5.6	-	40	5.0	160	7.2	1	3.5	1.2	10.5	265	IIIE
IIIF	var.	7.95	6.82	0.91	3.2	-	2.2	-	210	3.6	170	7.2	1.2	4.4	0.91	11	86	IIIF
IVA	Of	8.0	2.15	0.124	1.9	200[a]	0.88	0.8[a]	140	4.0	150	5.9	0.6	4.6	1.5	7.6	9	IVA
		8.4[a]	-	0.12[a]	2.0[a]	-	3.3[a]	1.0[b]	-	-	-	-	-	-	1.6[b]	-	-	IVA
		-	-	0.15[b]	1.8[b]	-	2.4[b]	-	-	-	-	-	-	-	-	-	-	IVA
IVB	D	17.1	0.221	0.0526	22	40 [a]	1	0.03[a]	87.7	7.4	12	27	3	12	0.15	1.1	1.5	IVB
		17.0[b]	-	0.053[a]	20[a]	-	3.0[a]	0[b]	-	-	-	-	-	-	-	-	-	IVB
		-	-	-	-	-	5.7[b]	-	-	-	-	-	-	-	-	-	-	IVB

From Mittlefehldt et al.,1998

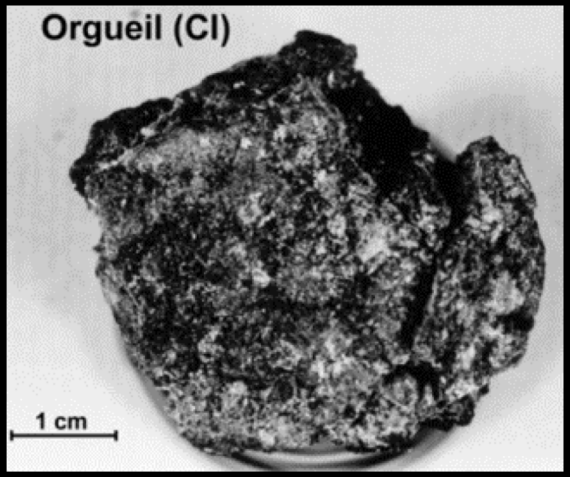
Carbon in Carbonaceous Chondrites



But….some have no chondrules, some have (almost) no carbon

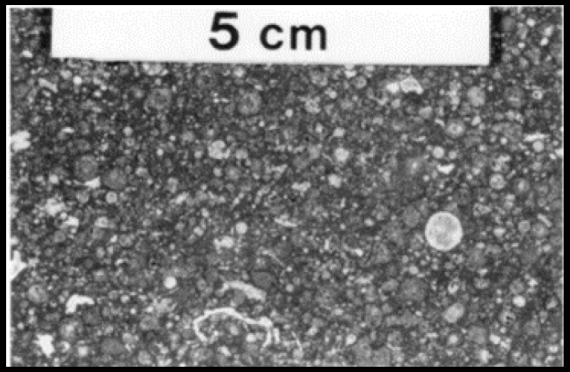
Volatile Rich Carbonaceous Chondrites

- CI, CM, C2, CR types…some essentially soggy dirt clods
- Mineralogy includes:
  - Hydrated clays (some ~80%)
  - Iron Oxides, Iron Sulfides
  - Olivine
  - Organics (carbon compounds)
  - Ice
- Weakest meteorites, some very weak ~1-50 MPs.



Anhydrous Carbonaceous Chondrites

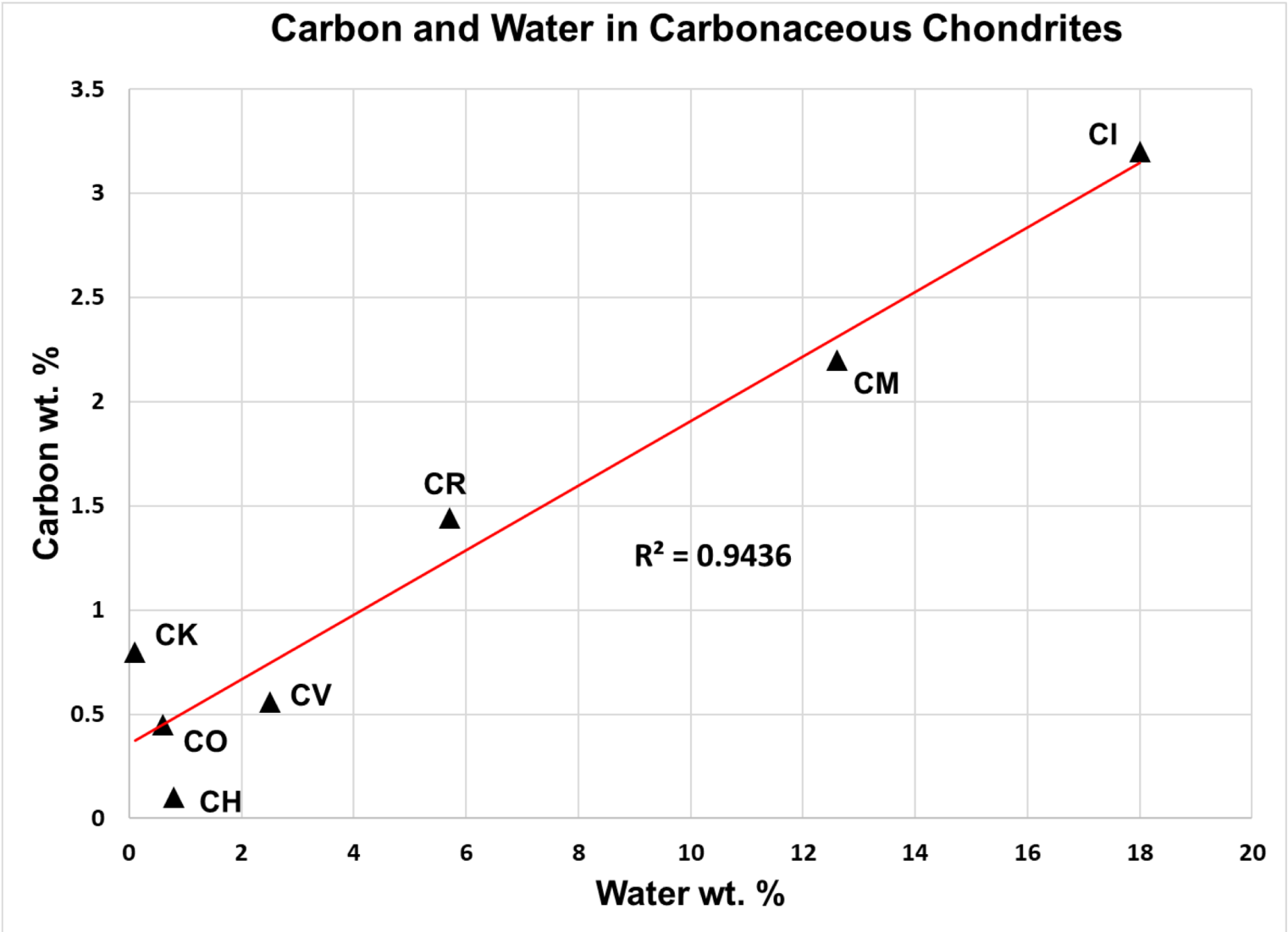
- CV, CO, CR, CK, CH
- Mineralogy much like ordinary chondrites (with chondrules)
- Mineralogy: olivine, pyroxene, metal, sulfides.
- Very strong (range up to 200 Mpa). Tough to break up.
- Highly depleted in volatiles.



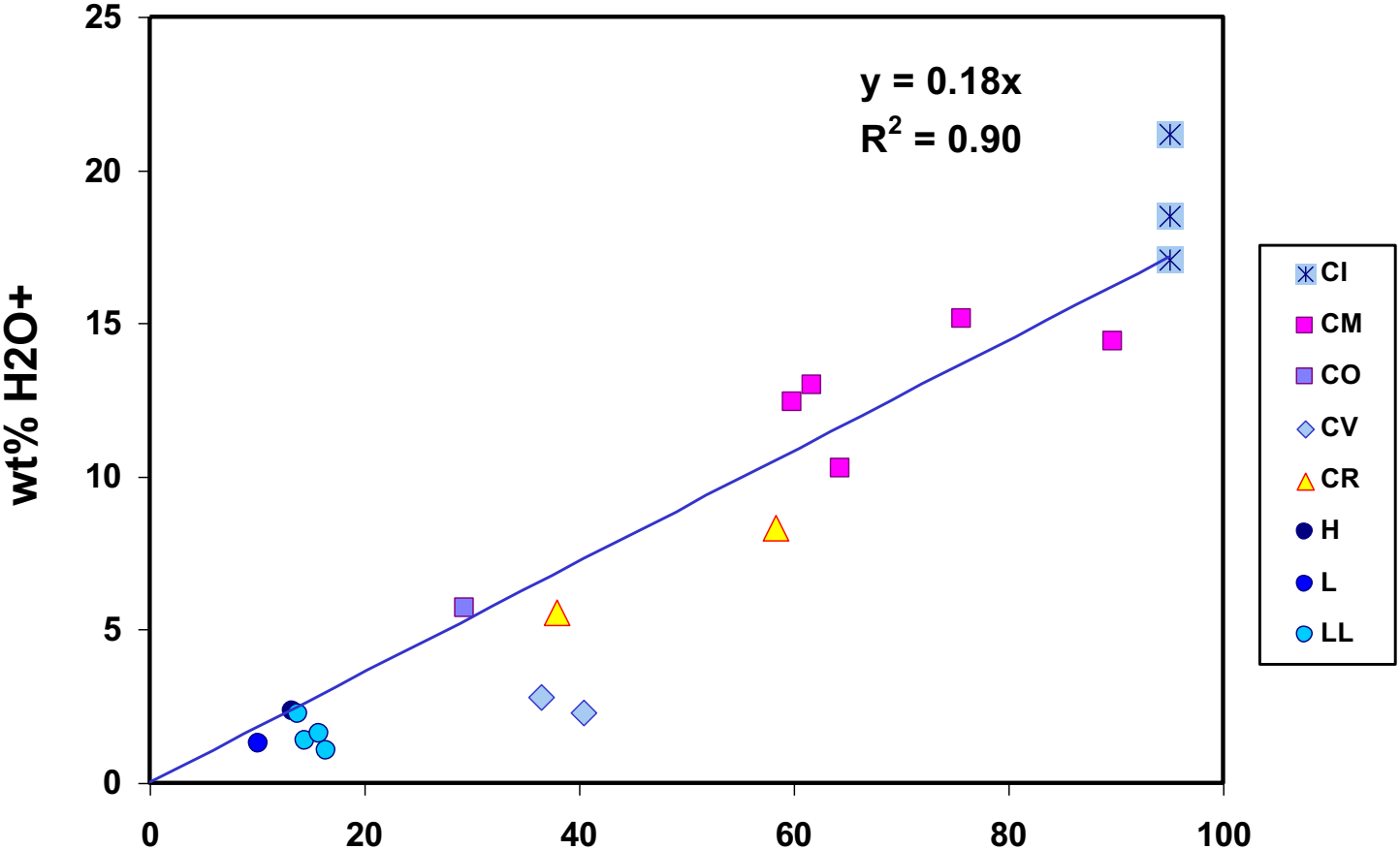
But not many have significant carbon

	carbonaceous chondrites							ordinary				enstatite	
	CI	CM	CO	CV	CK	CR	CH	H	L	LL	R	EL	EH
Si	10.5	12.9	15.9	15.6	15.1	15.3	13.3	16.9	18.5	18.9	15.8	18.6	16.7
Ti	0.042	0.058	0.078	0.098	0.13	0.11	0.047	0.060	0.063	0.062	0.05	0.058	0.045
Al	0.86	1.18	1.43	1.75	1.61	1.27	1.06	1.13	1.22	1.19	1.07	1.05	0.81
Cr	0.265	0.305	0.355	0.360	0.366	0.375	0.343	0.366	0.388	0.374	0.362	0.305	0.315
Fe	18.2	21.0	24.8	23.5	23.6	24.0	40.4	27.5	21.5	18.5	24.25	22.0	29.0
Mn	0.190	0.170	0.165	0.145	0.146	0.170	0.106	0.232	0.257	0.262	0.228	0.163	0.220
Mg	9.7	11.7	14.5	14.5	14.8	13.9	12.3	14.0	14.9	15.3	12.9	14.1	10.6
Ca	0.92	1.27	1.58	1.90	1.72	1.38	1.14	1.25	1.31	1.30	1.20	1.01	0.85
Na	0.49	0.41	0.41	0.33	0.319	0.323	0.182	0.64	0.70	0.70	0.659	0.580	0.680
K	0.056	0.040	0.035	0.031	0.029	0.030	0.021	0.078	0.083	0.079	0.068	0.074	0.080
P	0.102	0.090	0.104	0.099	0.043	0.122	~0.1	0.108	0.095	0.085	~0.07	0.117	0.200
Ni	1.07	1.20	1.40	1.34	1.27	1.36	2.45	1.60	1.20	1.02	1.44	1.30	1.75
Co	0.051	0.058	0.069	0.066	0.064	0.067	0.115	0.081	0.059	0.049	0.070	0.067	0.084
S	5.9	3.3	2.0	2.2	1.58	1.31	0.25	2.0	2.2	2.3	4.07	3.3	5.8
H_2O	18.0	12.6	0.6	2.5	0.8	5.7	0.1	–	–	–	–	–	–
C	3.2	2.2	0.45	0.56	~0.1	1.44	~0.8	0.11	0.09	0.12	0.058	0.36	0.40
O	30.0	32.0	36.5	34.8	35.5	31.2	25.6	35.7	37.7	40.0	37.3	31.0	28.0
Fe^o/Fe^{tot}	0.0	0.0	0.1	0.1	0.0	0.43	0.85	0.6	0.3	0.15	0.0	0.74	0.65
Ir(ppb)	460	595	735	760	767	642	1030	760	490	360	614	525	565
Au(ppb)	144	165	184	144	136	139	202	215	162	140	183	225	330

Wt. %, From Hutchison 2004

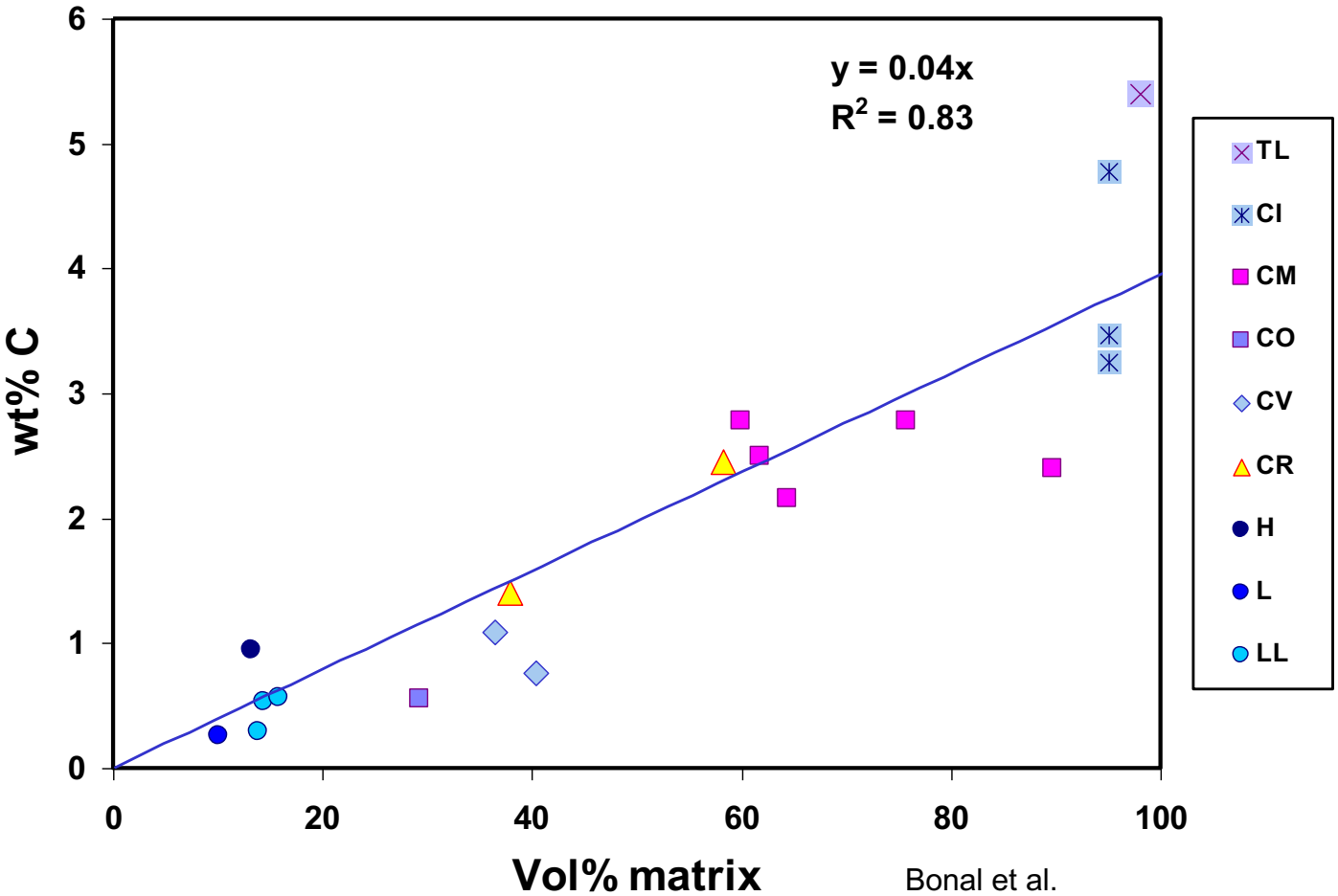

Carbon and Water in Carbonaceous Chondrites
Carbon wt. %
Water wt. %
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
CI
CM
CR
CK
CV
CO
CH
R² = 0.9436

The water (and carbon) is in the matrix



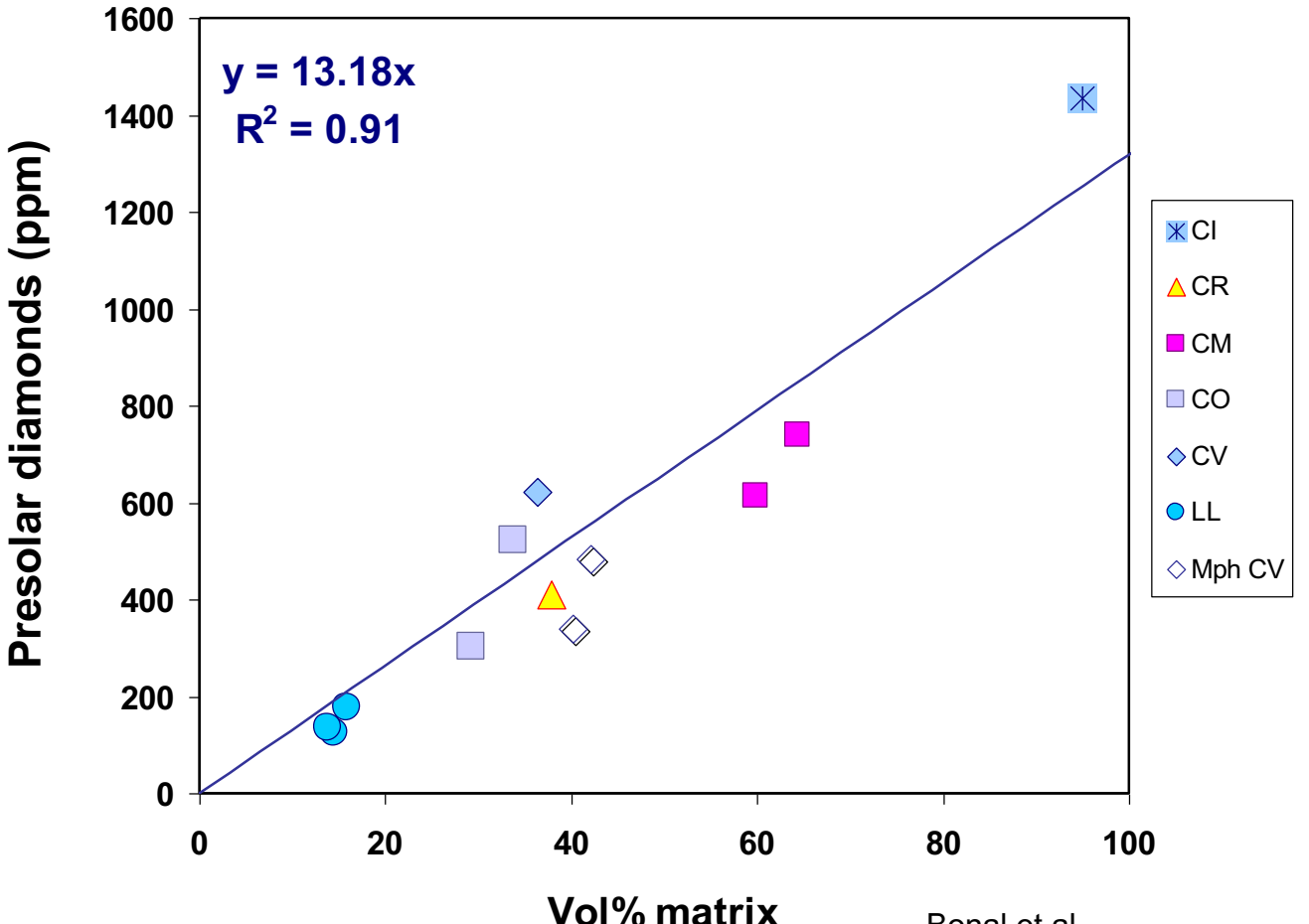
Bonal et al.

The water (and carbon) is in the matrix



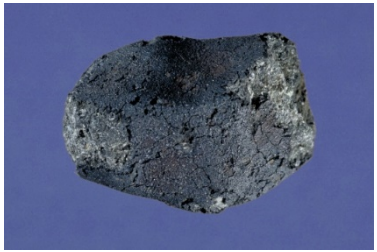
Bonal et al.

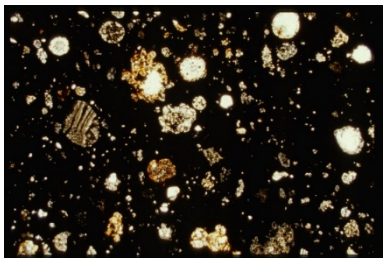
Other things in the matrix

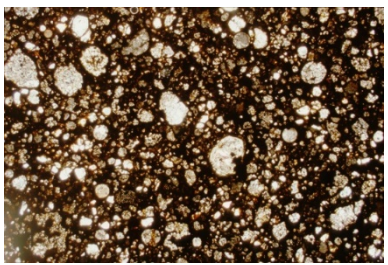


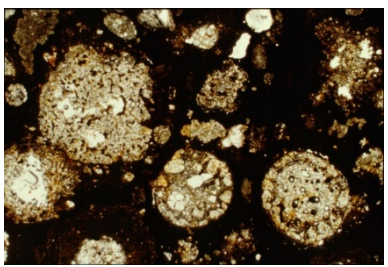
Bonal et al.

What is Matrix?









	% matrix
CI	>99
CM	70
CO	34
CV	40

Very fine-grained material

- In physical and chemical disequilibrium (Mg#, crystals and amorphous grains…)
- Rich in volatile elements, water, OH, clays
- Containing presolar grains and primitive organic compounds
- Low-temperature materials

Water in Volatile-Rich Carbonaceous Chondrites

- The "water" is in the form of OH (hydroxyl) in the crystal structure of phyllosilicates.
  - The high-temperature silicates (olivine) interact with melting ice and form alteration products (phyllosilicates).
  - Some CC's (i.e. CMs, CIs) are mostly alteration products.
- How does that work?
  - In the outer solar system things accrete as intimate mixtures of silicate dust, organics, and various ices.
  - These things are in huge chemical disequilibrium
  - If the ice melts then the silicates will react.
  - The amount of alteration depends on the original amount of water incorporated from the solar nebula

Mineralogy of Volatile-Rich CC's (wt.%)

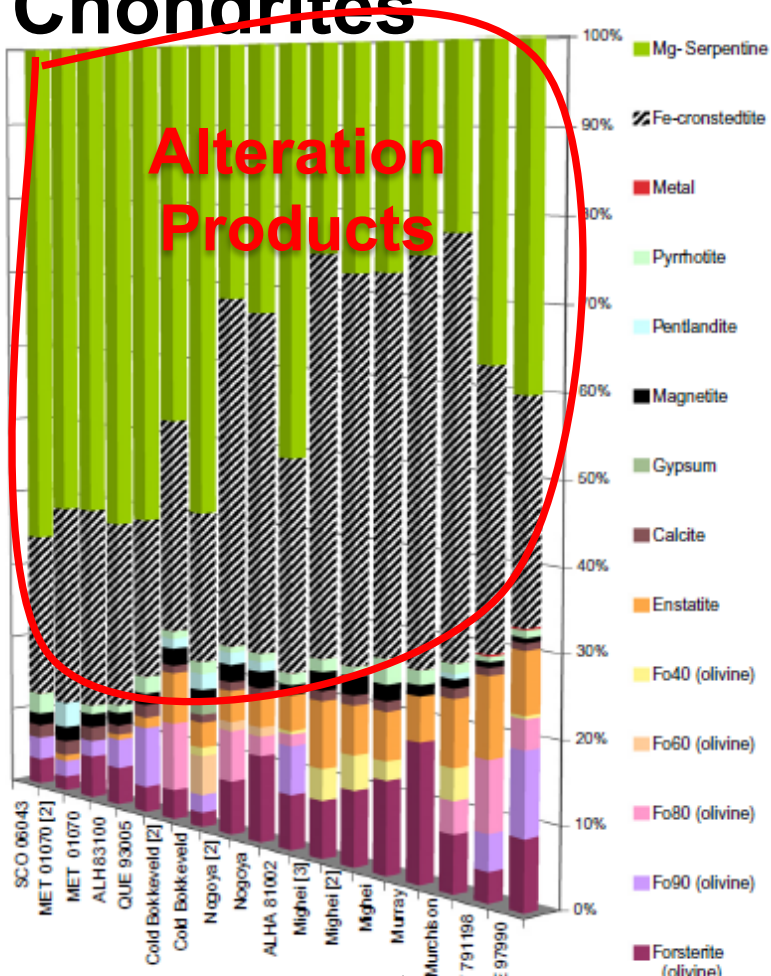
(Red are alteration minerals)

	CI-type	CM-type	CR-type	C2-type	CV-type
Olivine	7	11	32	25	80
Troilite	6.5	2.5	4	8.5	11
Pyroxene			28		7
Vermiculite	9				
Magnetite	13.5	1	14	22	1
Mg Serpentine	48	22	15	30.5	
Smectite	5			8	
Epsomite	6				
Kerogen	5	3.5	2	5	
Fe Serpentine		57			
Fe-Ni Metal			5		1
Total Alteration Products	**81.5**	**80**	**29**	**60.5**	**0**

CM Carbonaceous Chondrites

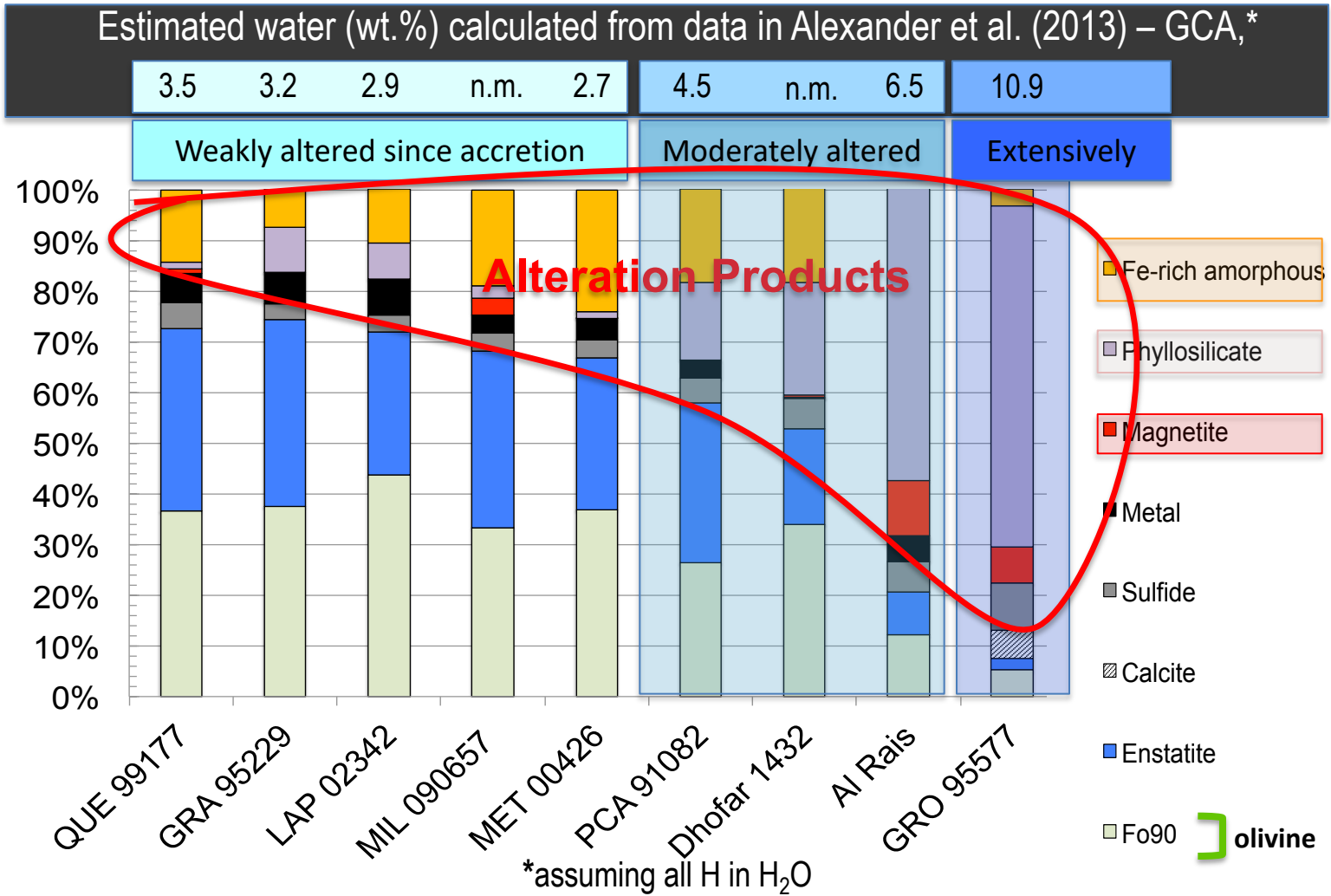
- **Hydrated carbonaceous chondrites (CI, CM, C2, CR) are rich in phyllosilicates….i.e. hydrated layered silicates.**

Sutters Mill (CM)

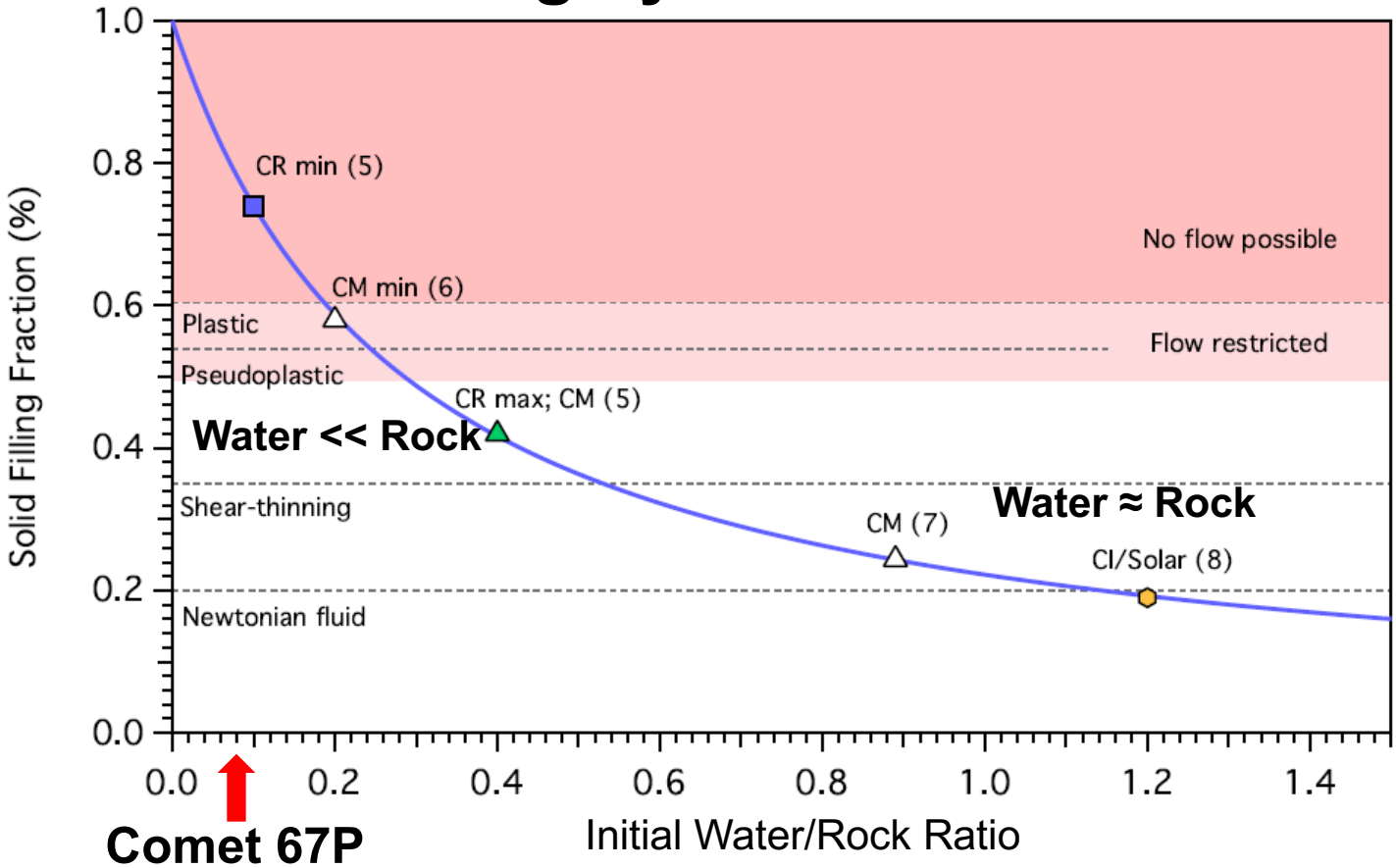


From Howard et al, 2011

Alteration in CR chondrites (modified from Howard et al. 2015 – LPSC)



The amount of original water can be highly variable…..

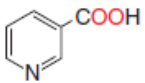
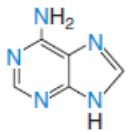
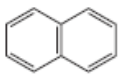
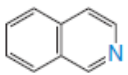
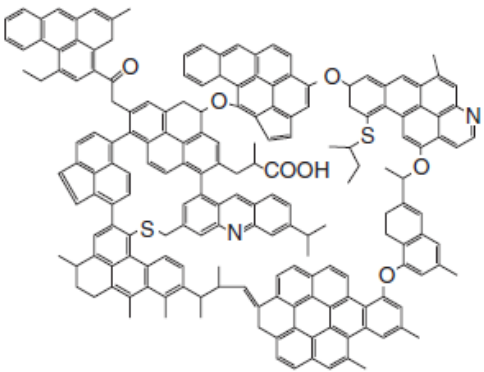


The Form of Carbon Compounds

Compound Class	Structure & Example Molecule	
Carboxylic acids	$H_3C—COOH$	Acetic acid
Amino acids	$H_3C–C(NH_2)(H)–COOH$	Alanine
Hydroxy acids	$H_3C–C(OH)(H)–COOH$	Lactic acid
Ketoacids	$H_3C–C(=O)–H$	Pyruvic acid
Dicarboxylic acids	$HOOC–C(H_2)–COOH$	Succinic acid
Sugar alcohols & acids	$H_2C(OH)–C(OH)(H)–CHO$	Glyceric acid
Aldehydes & Ketones	$H_3C–C(=O)–H$	Acetaldehyde
Amines & Amides	$H_3C·CH_2NH_2$	Ethyl amine

Pizzarello and Shock, 2010

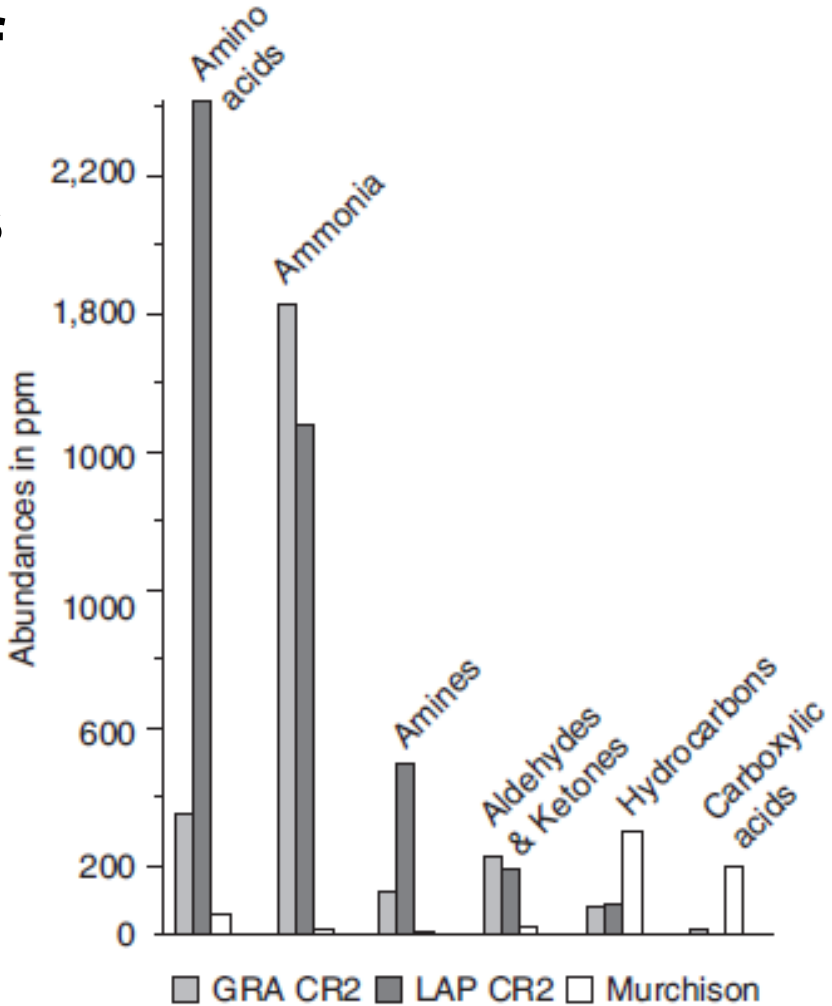
The Form of Carbon Compounds

Pyridine carb. acids		Nicotinic acid
Purines & Pyrimidines		Adenine
Hydrocarbons:		
Alyphatic	$H_3C–CH_2–CH_3$	Propane
Aromatic		Naphthalene
Polar		Isoquinoline
		Insoluble Material (estimated)

Pizzarello and Shock, 2010

The Form of Carbon Compounds

- **There are some distinct differences in organic abundances within carbonaceous chondrites.**



Pizzarello and Shock, 2010

To Wrap Up

- Carbon in meteorites is generally a very minor component….
- Essentially limited to two groups, volatile rich carbonaceous chondrites and Ureilites.
- In Ureilites carbon is in the matrix in the form of graphite and diamonds.
- In Carbonaceous Chondrites the carbon is in the matrix in the form of organics and graphite
  - Strongly correlated with water
  - Strongly correlated with pre-solar grains
  - Organics are highly variable and complex