Origin of solar systems: Organization

Lecture (KJ):	Student talks:
Introduction and overview Dense molecular clouds, photo-dissociation regions and protostars	Origin of the elements and Standard Abundance Distribution
Protoplanetary disks Equilibrium condensation of a solar nebula	Agglomeration of planetesimals and protoplanets
Meteorites and the early solar system	Isotope chronology of meteorites and oxygen isotopes
Origin of giant planets	Extrasolar planets
Comets and the early solar system	Transneptunian Objects

Meteorites and the Early Solar System

- Relevance of meteorite study to the origin of solar systems
- Fundamentals on mineralogy and thermal processing of cosmic matter: The Bowen series
- Meteorite classification
- Standard abundance distribution
- Chemical and mineralogical properties of meteorites
- Ages and time scales
- Possible origin of chondrules and CAIs

Meteorites:

Meteoride → meteor → meteorite
“Falls” or “finds”
What can we learn from the study of meteorites about the origin of solar systems?

- Meteorites of CI type closely represent the Standard Abundance Distribution (“cosmic abundance”)
- Some meteorites are related to planets (Mars) or the Earth’s moon.
- Some may represent planetesimals from the early time of solar system formation or fragments of them.
- Many of them are broken pieces from asteroids. Depending on their size asteroids may be differentiated or not.
- But: Meteorites are very unlikely to come from the outer solar system, so the information contained in them refers to the solar system inside of Jupiter’s orbit.

Now we turn to a brief introduction into “astro-mineralogy”

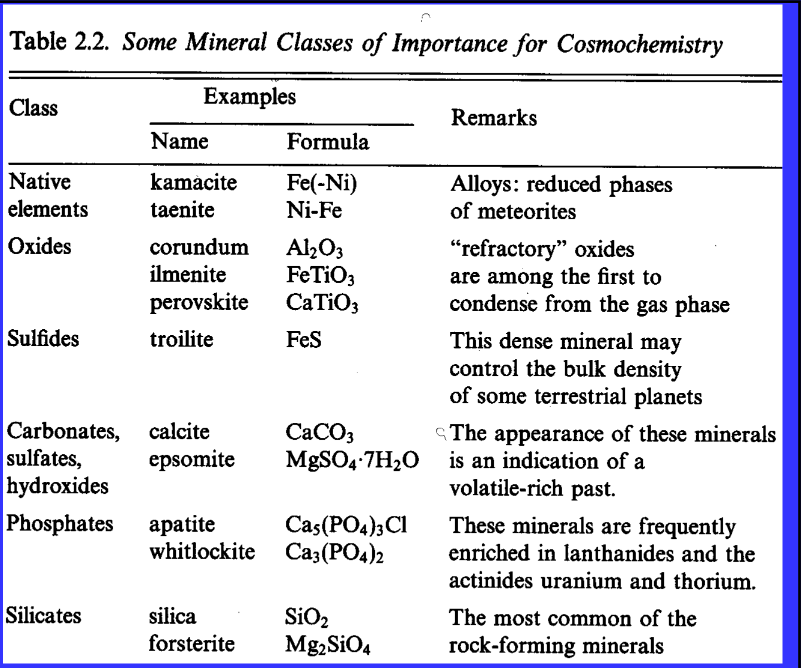

Table 2.2. *Some Mineral Classes of Importance for Cosmochemistry*

Class	Examples		Remarks
	Name	Formula	
Native elements	kamacite taenite	Fe(-Ni) Ni-Fe	Alloys: reduced phases of meteorites
Oxides	corundum ilmenite perovskite	Al_2O_3 $FeTiO_3$ $CaTiO_3$	“refractory” oxides are among the first to condense from the gas phase
Sulfides	troilite	FeS	This dense mineral may control the bulk density of some terrestrial planets
Carbonates, sulfates, hydroxides	calcite epsomite	$CaCO_3$ $MgSO_4 \cdot 7H_2O$	The appearance of these minerals is an indication of a volatile-rich past.
Phosphates	apatite whitlockite	$Ca_5(PO_4)_3Cl$ $Ca_3(PO_4)_2$	These minerals are frequently enriched in lanthanides and the actinides uranium and thorium.
Silicates	silica forsterite	SiO_2 Mg_2SiO_4	The most common of the rock-forming minerals

This and the following slides from Cowley, *An Introduction to Cosmochemistry*, Cambridge Univ. Press 1995

Oxides:

Al_2O_3 (Corundum), a common refractory (high melting point) oxide

$CaTiO_3$ (perovskites) also refractory

Spinel one divalent, two trivalent cations like $Fe^{2+}(Fe^{3+})_2O_4$, $MgAl_2O_4$

SiO_2, silicon dioxide (quarz, tridymite, cristobalite), forms only after processing

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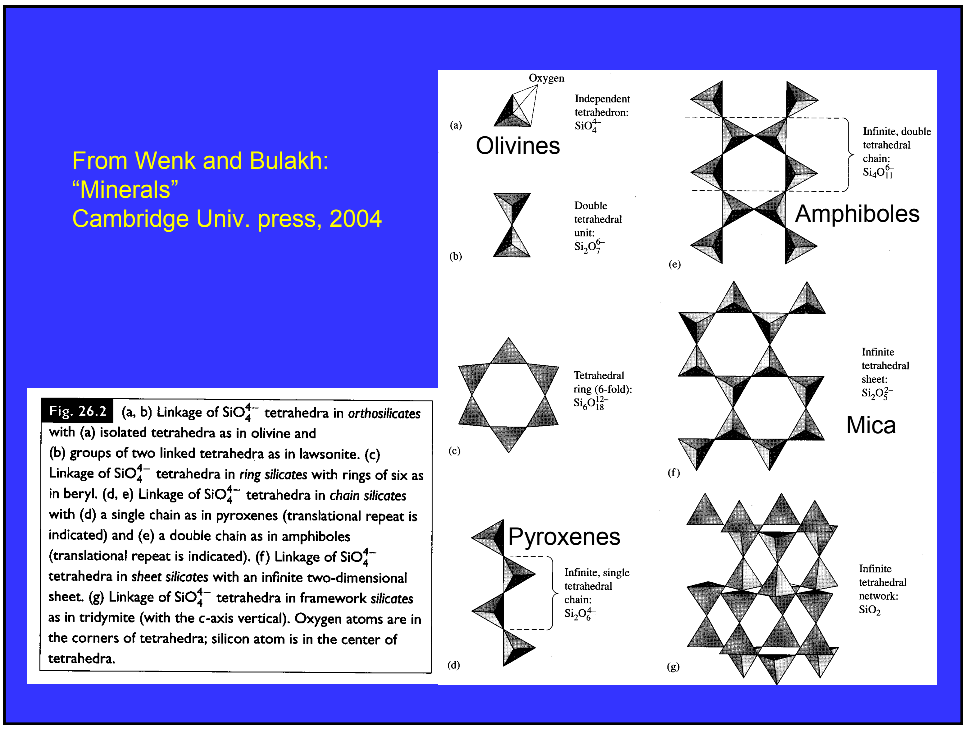
Olivines (refractory, common in “primitive solids”)

Fe_2SiO_4 (fayalite)
Mg_2SiO_4 (forsterite)
Most frequently we find mixtures of the two.

They are nesosilicate (nes = island, isolated tetrahedra)

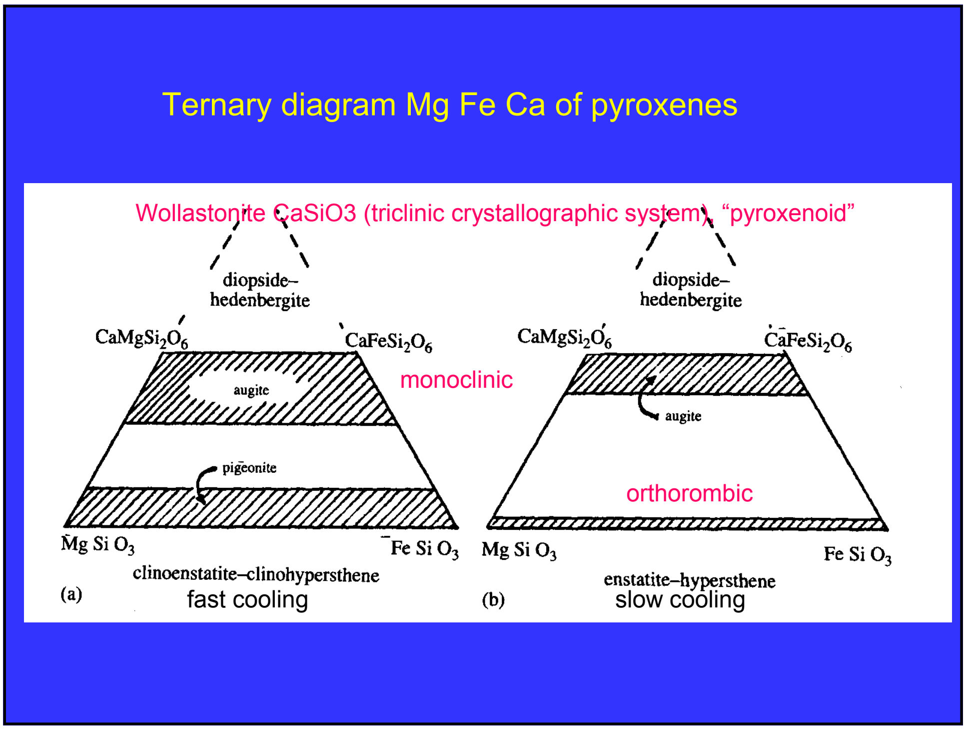
Pyroxenes (more processed than olivines)

Pyroxenes (inosilicates) form single or double chains of tetrahedra. As the oxygen atoms are shared between adjacent tetrahedra, the chemical formula is SiO_3 or Si_2O_6.
$MgSiO_3$ or $Mg_2Si_2O_6$ (enstatite, as compared to forsterite there is one more SiO_2 “anion” added)



From Wenk and Bulakh:
“Minerals”
Cambridge Univ. press, 2004

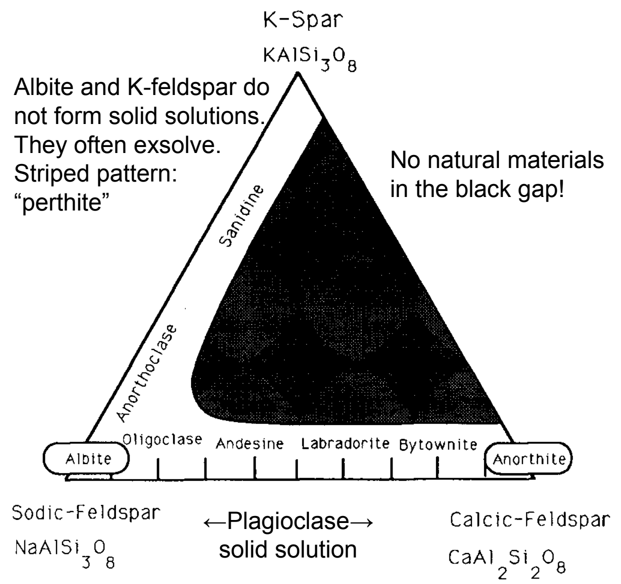
Fig. 26.2 (a, b) Linkage of SiO_4^{4-} tetrahedra in *orthosilicates* with (a) isolated tetrahedra as in olivine and (b) groups of two linked tetrahedra as in lawsonite. (c) Linkage of SiO_4^{4-} tetrahedra in *ring silicates* with rings of six as in beryl. (d, e) Linkage of SiO_4^{4-} tetrahedra in *chain silicates* with (d) a single chain as in pyroxenes (translational repeat is indicated) and (e) a double chain as in amphiboles (translational repeat is indicated). (f) Linkage of SiO_4^{4-} tetrahedra in *sheet silicates* with an infinite two-dimensional sheet. (g) Linkage of SiO_4^{4-} tetrahedra in framework *silicates* as in tridymite (with the *c*-axis vertical). Oxygen atoms are in the corners of tetrahedra; silicon atom is in the center of tetrahedra.



Ternary diagram Mg Fe Ca of pyroxenes

The feldspars:

most common on Earth: “dirt”
Add one more SiO_2 unit to the pyroxenes!



Albite and K-feldspar do not form solid solutions. They often exsolve. Striped pattern: “perthite”

No natural materials in the black gap!

←Plagioclase→
solid solution

Figure 2.5. The Feldspar Ternary Diagram (schematic).

Processing of minerals by partial melting and weathering

The mineralogy of natural materials provides a *flawed but useful* guide to their history → the Bowen reaction series.

On Earth, rocks that are extruded through faults and fissure in the Earth’s crust are often dominated by olivine. Olivine will react with a liquid rich in SiO_2 to form the pyroxene (clino)enstatite.

Weathering:

Olivines → serpentines → clay minerals
Pyroxenes → amphiboles → micas → clay minerals

Partial melting:
In coexisting melt and solidus the chemical composition frequently is different. If the melt escapes (e.g. erupts as lava) the chemical composition of the remaining solidus is altered.

Example:

Plagioclase forms a solid solution, but this is not necessary for a differentiation to take place. Minerals that are more easily melted will accumulate in the melt. The same is true for trace elements (as we will see later).

2.6 History: The Bowen Series

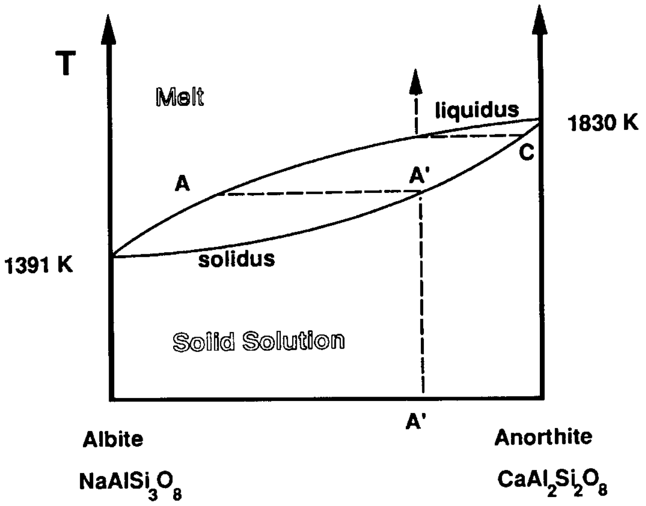


Figure 2.7. Phase Diagram for Plagioclase Feldspar (schematic).

The Bowen Series:

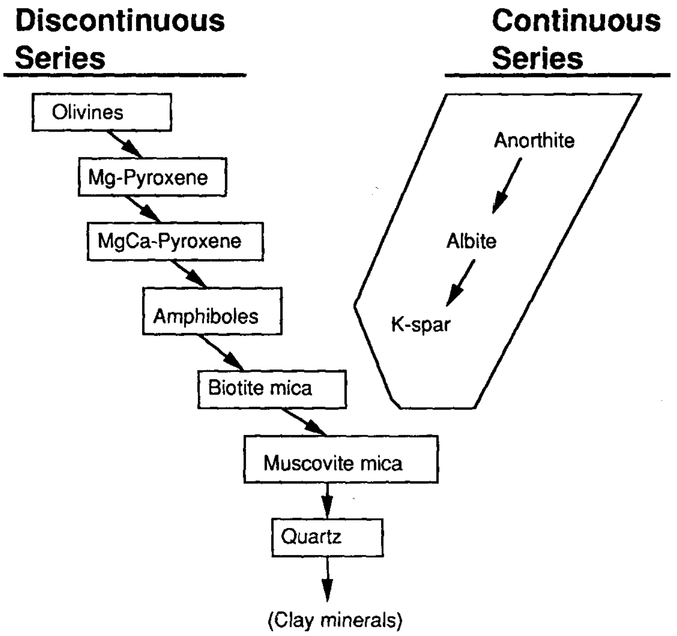


Figure 2.6. The Reaction Series.

Siderophiles ♥ metal
Chalkophiles ♥ sulphur
Lithophiles ♥ silicate

weight percent →

part per million →

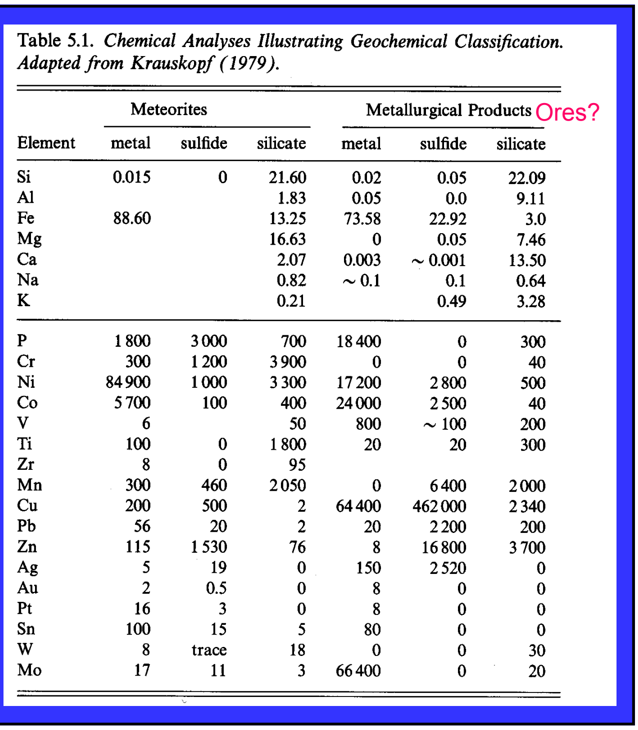


Table 5.1. *Chemical Analyses Illustrating Geochemical Classification. Adapted from Krauskopf (1979).*

	Meteorites			Metallurgical Products Ores?		
Element	metal	sulfide	silicate	metal	sulfide	silicate
Si	0.015	0	21.60	0.02	0.05	22.09
Al			1.83	0.05	0.0	9.11
Fe	88.60		13.25	73.58	22.92	3.0
Mg			16.63	0	0.05	7.46
Ca			2.07	0.003	~ 0.001	13.50
Na			0.82	~ 0.1	0.1	0.64
K			0.21		0.49	3.28
P	1 800	3 000	700	18 400	0	300
Cr	300	1 200	3 900	0	0	40
Ni	84 900	1 000	3 300	17 200	2 800	500
Co	5 700	100	400	24 000	2 500	40
V	6		50	800	~ 100	200
Ti	100	0	1 800	20	20	300
Zr	8	0	95			
Mn	300	460	2 050	0	6 400	2 000
Cu	200	500	2	64 400	462 000	2 340
Pb	56	20	2	20	2 200	200
Zn	115	1 530	76	8	16 800	3 700
Ag	5	19	0	150	2 520	0
Au	2	0.5	0	8	0	0
Pt	16	3	0	8	0	0
Sn	100	15	5	80	0	0
W	8	trace	18	0	0	30
Mo	17	11	3	66 400	0	20

Siderophile – lithophile distinction:

Note: free energy for oxidation similar to free energy for formation of silicates

If competing for oxygen,
Fe will win over Ni and
Mg will win over Fe.

If there was, at one time, parent magma consisting of silicates as well as Fe, the siderophiles would be partitioned, preferentially, into the reduced phase, as the melt froze.
It would be desirable, especially for the trace elements, to know the quantitative ratios, the so-called partition coefficients.

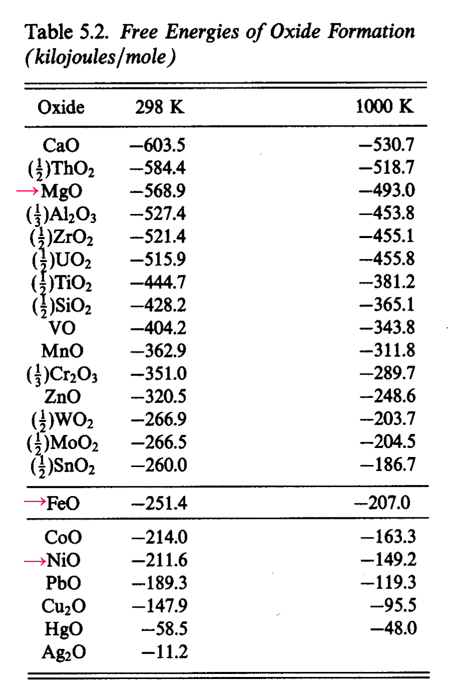


Table 5.2. *Free Energies of Oxide Formation (kilojoules/mole)*

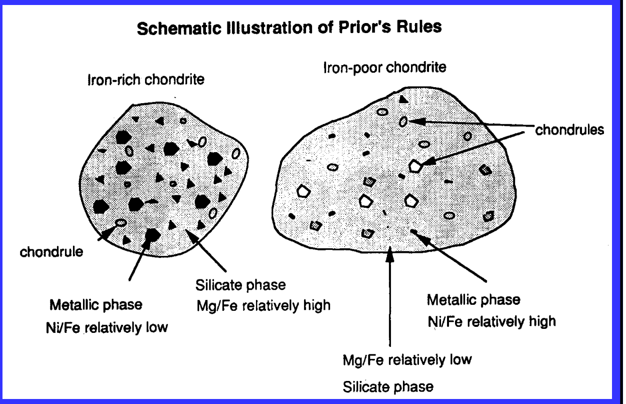
Oxide	298 K	1000 K
CaO	−603.5	−530.7
$(\frac{1}{2})ThO_2$	−584.4	−518.7
→ MgO	−568.9	−493.0
$(\frac{1}{3})Al_2O_3$	−527.4	−453.8
$(\frac{1}{2})ZrO_2$	−521.4	−455.1
$(\frac{1}{2})UO_2$	−515.9	−455.8
$(\frac{1}{2})TiO_2$	−444.7	−381.2
$(\frac{1}{2})SiO_2$	−428.2	−365.1
VO	−404.2	−343.8
MnO	−362.9	−311.8
$(\frac{1}{3})Cr_2O_3$	−351.0	−289.7
ZnO	−320.5	−248.6
$(\frac{1}{2})WO_2$	−266.9	−203.7
$(\frac{1}{2})MoO_2$	−266.5	−204.5
$(\frac{1}{2})SnO_2$	−260.0	−186.7
→ FeO	−251.4	−207.0
CoO	−214.0	−163.3
→ NiO	−211.6	−149.2
PbO	−189.3	−119.3
Cu_2O	−147.9	−95.5
HgO	−58.5	−48.0
Ag_2O	−11.2	

Sources: Robie, Hemingway, and Fisher (1978), *HCP*, and *JANAF*.

Prior's rules (1916):

left:
Ni wins over Fe for reduced phase. If Mg content is low in the matrix, most Fe can go into matrix.

right:
Mg wins over Fe in silicate matrix. If Mg is high in matrix, Fe must remain in reduced phase.



Mobility of ions:

The larger the ion radius, the more difficult it becomes to adapt an ion into a crystal grid.

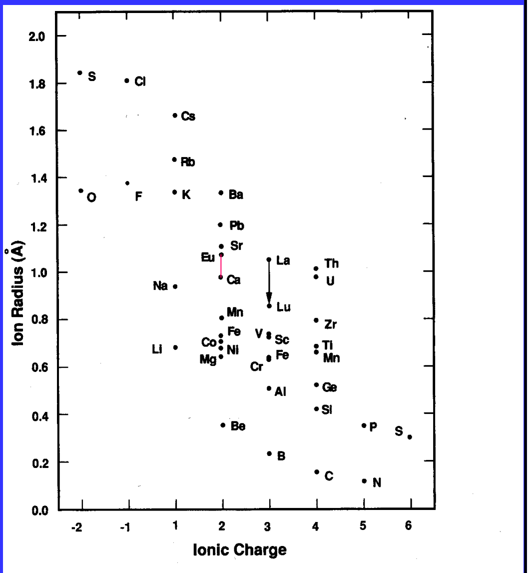
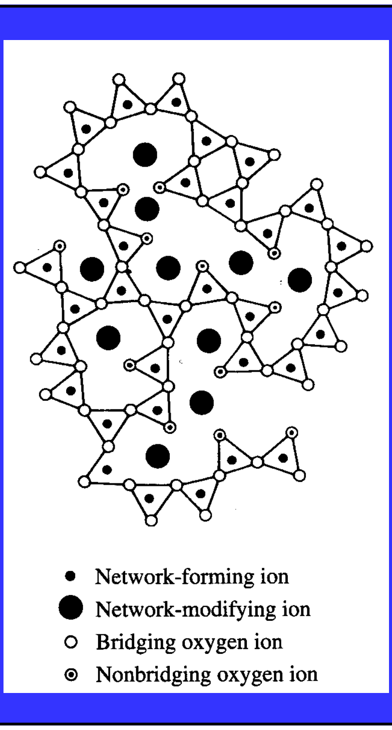


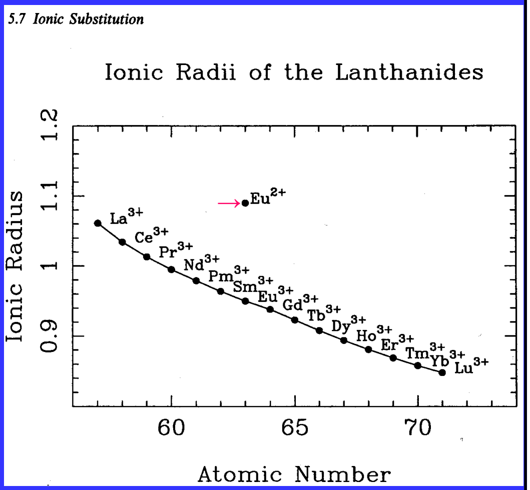
Figure 5.7. Ionic Radii and Valences. Adapted from Berry and Mason (1959).



Europium on the moon in highland rocks and mare basalts, 1

In contrast to the usual trend the radii of the Lanthanide ions decrease with atomic number (an inner atomic shell is being filled).

Eu^{++} is in radius and valence similar to Ca^{++} and therefore easily implemented into anorthite (calthic feldspar $CaAl_2Si_2O_8$).



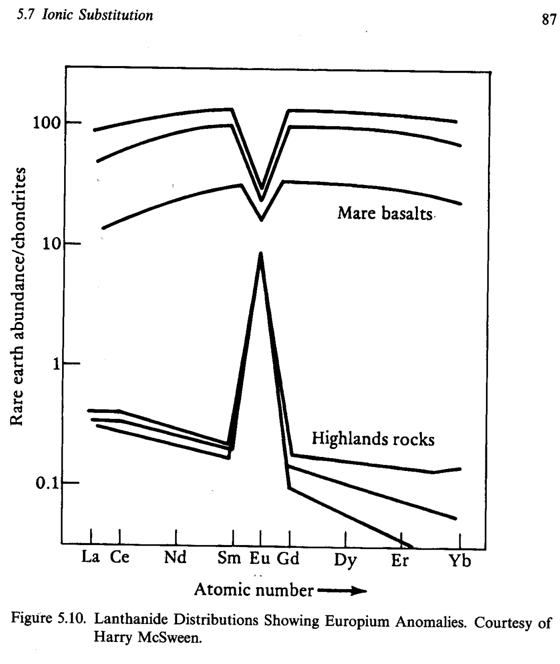
Europium on the moon in highland rocks and mare basalts

Note that in the figure we plot rare earth abundance/chondrites!

When the highland rocks formed out of a melt Eu was enriched in its divalent form because of its similarity to Ca.

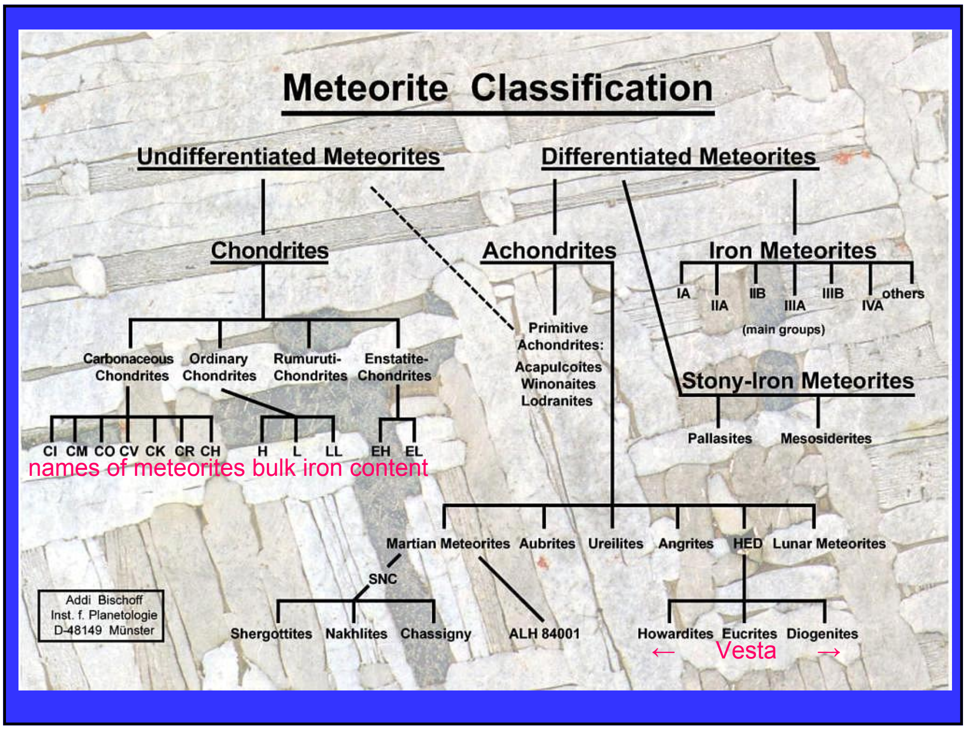
The other lanthanides are more abundant the larger their radius.

When the lunar maria formed, the highland rocks partly remelted. The lanthanides except of Eu^{++} are more abundant in the melt.



5.7 Ionic Substitution 87

Figure 5.10. Lanthanide Distributions Showing Europium Anomalies. Courtesy of Harry McSween.



Meteorite Classification

Undifferentiated Meteorites

Chondrites

Carbonaceous Chondrites: CI CM CO CV CK CR CH

Ordinary Chondrites: H L LL

Rumuruti-Chondrites

Enstatite-Chondrites: EH EL

names of meteorites bulk iron content

Differentiated Meteorites

Achondrites

Primitive Achondrites:
Acapulcoites
Winonaites
Lodranites

Martian Meteorites (SNC): Shergottites, Nakhlites, Chassigny; ALH 84001

Aubrites

Ureilites

Angrites

HED: Howardites, Eucrites, Diogenites

← Vesta →

Lunar Meteorites

Iron Meteorites

IA IIA IIB IIIA IIIB IVA others

(main groups)

Stony-Iron Meteorites

Pallasites

Mesosiderites

Addi Bischoff
Inst. f. Planetologie
D-48149 Münster

The following slides (if not indicated otherwise) are from

Krot et al. “Classification of Meteorites”, in
Treatise on Geochemistry Vol. 1 “Meteorites, Comets and Planets”, pp 83-128
Elsevier 2005

Chondrites have chondrules, with exception of CI.

Condrules are typically submm-sized spherules believed to have been molten droplets in the solar nebula, formed by melting of dust in a brief, local heating event.

“Carbonaceous” somewhat of a misnomer, as only CI, CM and CR chondrites are significantly enriched in carbon.

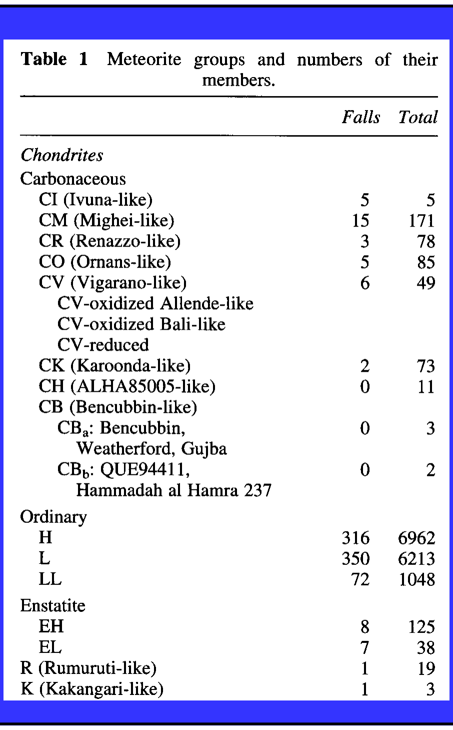


Table 1 Meteorite groups and numbers of their members.

	Falls	*Total*
Chondrites		
Carbonaceous		
CI (Ivuna-like)	5	5
CM (Mighei-like)	15	171
CR (Renazzo-like)	3	78
CO (Ornans-like)	5	85
CV (Vigarano-like)	6	49
CV-oxidized Allende-like		
CV-oxidized Bali-like		
CV-reduced		
CK (Karoonda-like)	2	73
CH (ALHA85005-like)	0	11
CB (Bencubbin-like)		
CB_a: Bencubbin, Weatherford, Gujba	0	3
CB_b: QUE94411, Hammadah al Hamra 237	0	2
Ordinary		
H	316	6962
L	350	6213
LL	72	1048
Enstatite		
EH	8	125
EL	7	38
R (Rumuruti-like)	1	19
K (Kakangari-like)	1	3

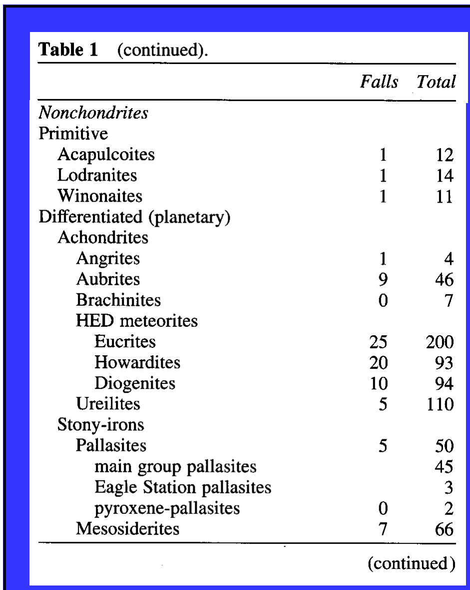


Table 1 (continued).

	Falls	*Total*
Nonchondrites		
Primitive		
Acapulcoites	1	12
Lodranites	1	14
Winonaites	1	11
Differentiated (planetary)		
Achondrites		
Angrites	1	4
Aubrites	9	46
Brachinites	0	7
HED meteorites		
Eucrites	25	200
Howardites	20	93
Diogenites	10	94
Ureilites	5	110
Stony-irons		
Pallasites	5	50
main group pallasites		45
Eagle Station pallasites		3
pyroxene-pallasites	0	2
Mesosiderites	7	66

(continued)

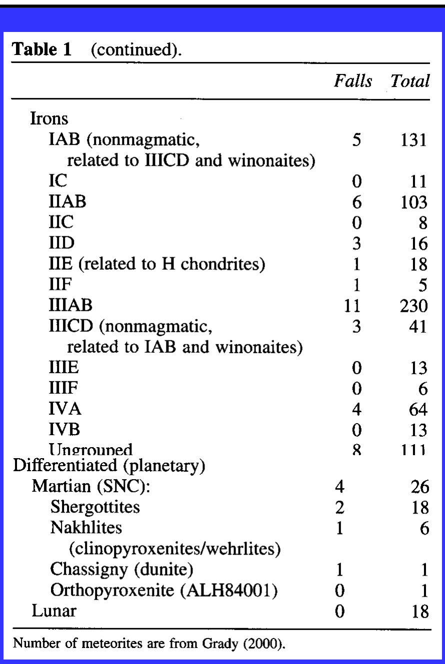


Table 1 (continued).

	Falls	*Total*
Irons		
IAB (nonmagmatic, related to IIICD and winonaites)	5	131
IC	0	11
IIAB	6	103
IIC	0	8
IID	3	16
IIE (related to H chondrites)	1	18
IIF	1	5
IIIAB	11	230
IIICD (nonmagmatic, related to IAB and winonaites)	3	41
IIIE	0	13
IIIF	0	6
IVA	4	64
IVB	0	13
Ungrouped	8	111
Differentiated (planetary)		
Martian (SNC):	4	26
Shergottites	2	18
Nakhlites (clinopyroxenites/wehrlites)	1	6
Chassigny (dunite)	1	1
Orthopyroxenite (ALH84001)	0	1
Lunar	0	18

Number of meteorites are from Grady (2000).

Taxonomy – beware of circular arguments!

Taxonomy (getting order into a set of observations by grouping them into clusters) is a man made process.

If we find regularity in a taxonomic system this may mean two things:

1. There is indeed some systematics in the observed data
2. The classifying scientists have done their job well.

Summary of petrographic properties of chondritic meteorites

	Carbonaceous						
	CM	*CO*	*CR*	*CH*	*CB*	*CV*	*CK*
CAI + AOA (vol.%)	5	13	0.5	0.1	<0.1	10	4
chd (vol.%)	20	48	50–60	~70	30–40	45	15
matrix (vol.%)	70	34	30–50	5	<5	40	75
metal (vol. %)	0.1	1–5	5–8	20	60–70	0–5	<0.01
chd, mean diam. mm	0.3	0.15	0.7	0.02	0.1–20	1	0.7

	Ordinary			*Enstatite*		*Additional*	
	H	*L*	*LL*	*EH*	*EL*	*K*	*R*
CAI + AOA (vol.%)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
chd (vol.%)	60–80	60–80	60–80	60–80	60–80	27	>40
matrix (vol.%)	10–15	10–15	10–15	<0.1	<0.1	60	30
metal (vol. %)	8.4	4.1	2.0	10.1	10.2	7.4	<0.1
chd, mean diam. mm	0.3	0.7	0.9	0.2	0.6	0.6	0.4

CAI = Calcium-Aluminum-Inclusion; AOA = amoeboid olivine aggregate
chd = chondrule

CI (Ivuna) meteorites

have an element abundance very close to solar and are considered Standard Abundance Distribution

The noble gases have left the meteorites.

- Li is easily destroyed in stars.
- Noble gases cannot form compounds and therefore are difficult to retain in meteorites.
- HCNO partially condensed (hydrated silicates, carbonate minerals, organic matter, solid carbon.

Whitted: "Dust in the galactic environment", London 1992.

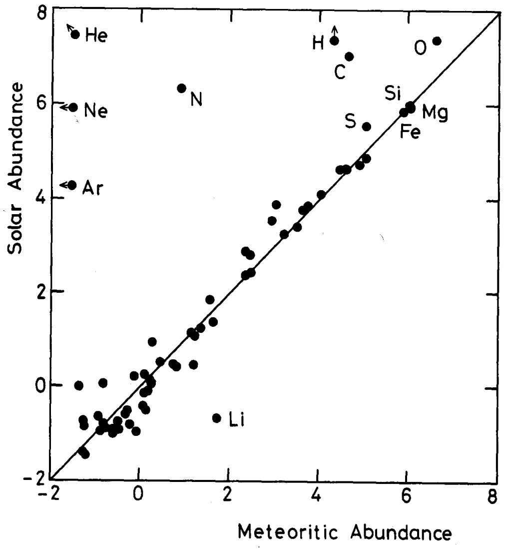
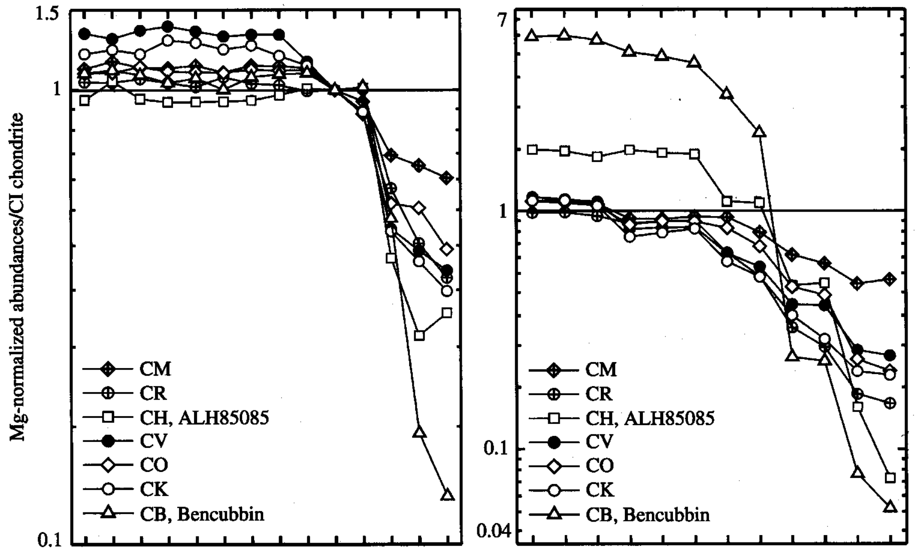


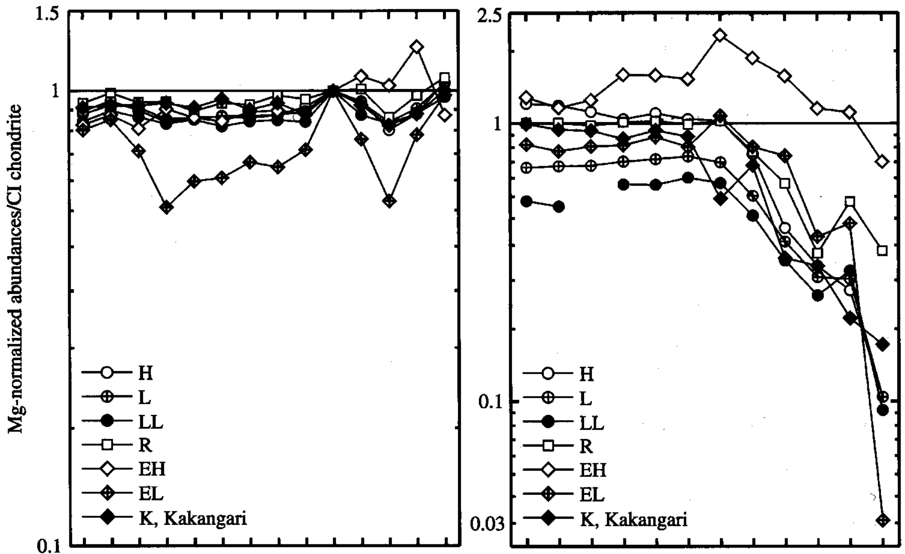
Figure 2.2 The correlation of abundances in the solar atmosphere and those in a typical carbonaceous chondrite. Abundances are by number, logarithmic on the Si = 6 scale. The straight line represents exact agreement.

Carbonaceous chondrites: lithophile and siderophile element abundances



Some systematics in chemical abundance recognizable.
Na, K are volatile and therefore less abundant in the later (more processed) classes.

Non-carbonaceous chondrites: lithophile and siderophile element abundances



Like in previous viewgraph also in this one lithophile and siderophile elements show volatility controlled abundance patterns.

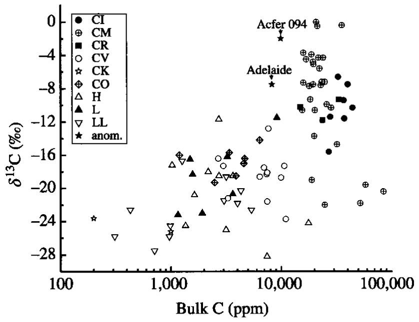


Figure 5 Bulk carbon contents (ppm) versus δ^{13}C (‰) in chondrites (sources Kerridge, 1985; Grady and Pillinger, 1986).

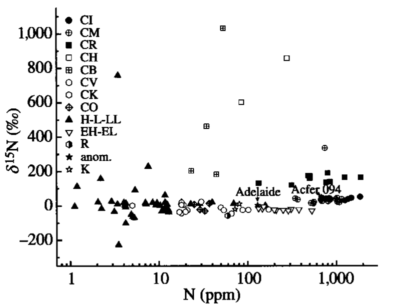


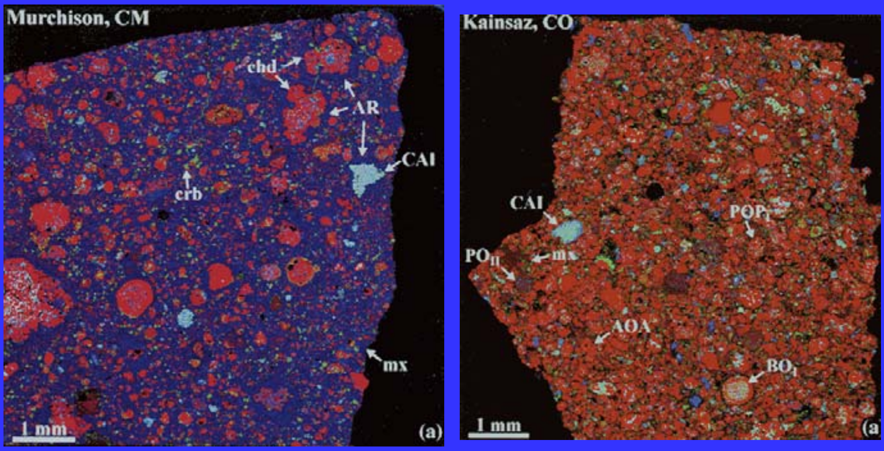
Figure 6 Bulk nitrogen contents (ppm) versus δ^{15}N (‰) in chondrites (sources Kerridge, 1985; Grady and Pillinger, 1990; Hashizume and Sugiura, 1995; Sugiura, 1995).

Nitrgen abundances and isotopic compositions can differentiate most of the existing chondrite groups. Carbon abundance and isotopic compositions can differentiate only CI and Mighei-like carbonaceous chondrite groups.

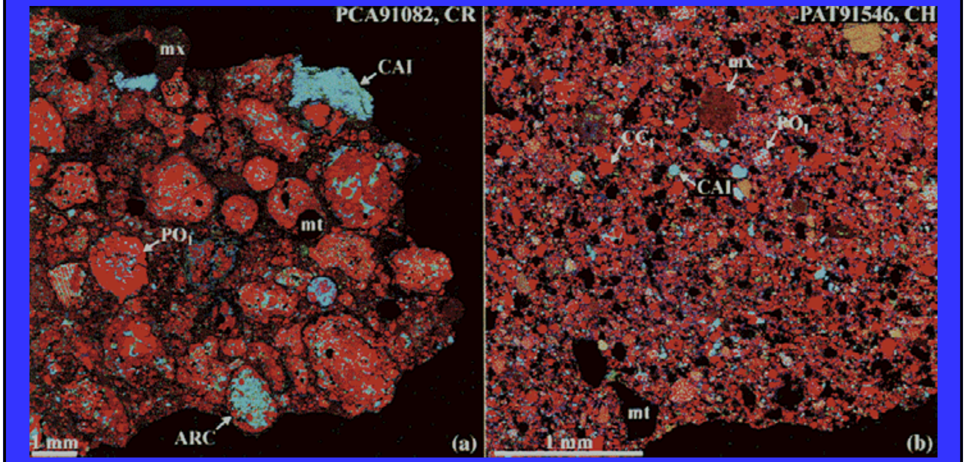
Calcium-aluminum-rich inclusions (CAIs):

- few µm < size < exceeding 1 cm
- found in all types of primitive chondrites but are rare in all but the CV carbonaceous chondrites
- bulk chemical composition = most refractory 5% of condensable solar matter
- May be direct condensates from the nebular gas, followed, in many cases, by further chemical and isotopic interaction with the gas.
- Radiometric ages measured with high precision = 4.567 x 10^9 years. Solidification earlier than any other solar system rocks.
- Oxygen isotope abundances may provide the best guide to the composition of the nebular gas

Elemental maps: Mg – red, Ca – green, Al - blue

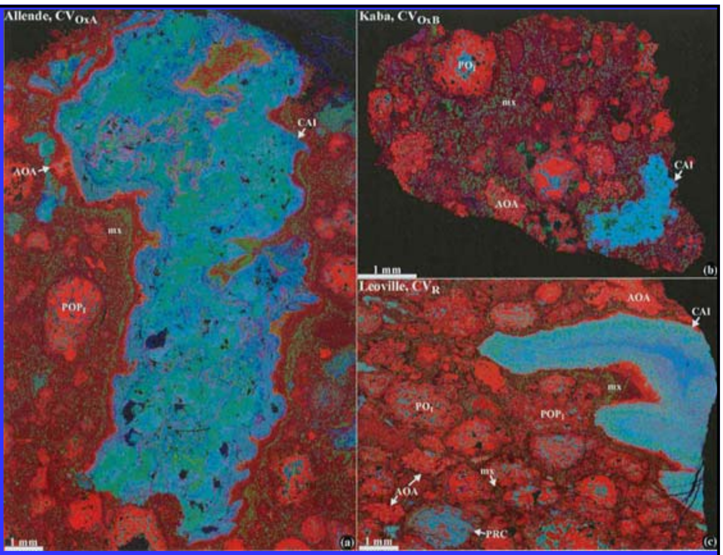


M: Carbonate rich
AR = accretionary rim; CAI = calcium aluminum rich inclusion (oldest);
chd = chondrule; crb = carbonates; mx = matrix; ARC anorthite-rich chondrule
AOA = amoeboid olivine aggregate; BO = barred olivine chondrule;
PO(P)$_{I,II}$ = type I (II) porphyritic olivine (pyroxene) chondrule.



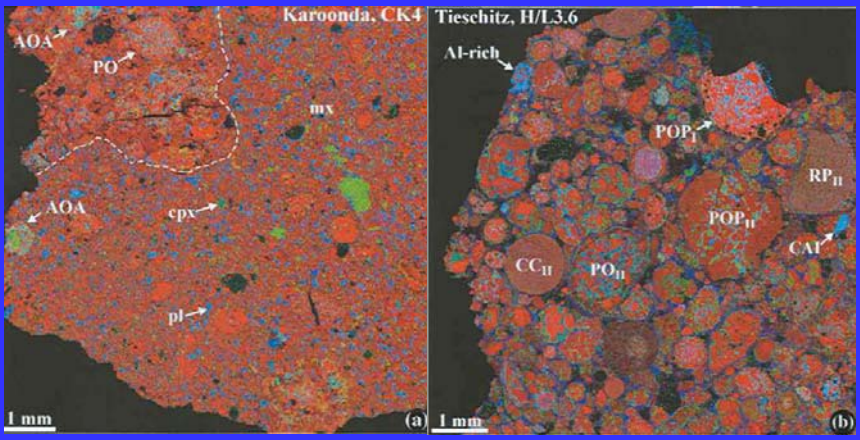
Larger chondrules

Combined elemental maps of **CV carbonaceous chondrites**:
a: Allende (CV$_{OxA}$),
b Kaba (CV$_{OxB}$),
c Leoville (CV$_{R}$).
The CV chondrites contain large CAIs, AOAs, and chondrules, and fine-grained matrix. Most chondrules have porphyritic textures and mg-rich compositions; plagioclase-rich chondrules (PRCs) are relatively common.



The CV matrices contain abundant secondary Ca-, Fe-rich pyroxenes (green spots). The Kaba martix is hydrated; martices in Leoville and Allende are anhydrous. Image of the Allende meteorite is not representative: large CAIs are relatively rare.

Carbonaceous chondrite breccia Karoonda Ordinary chondrite Tieschitz



Remember:
Fayalite = Fe_2SiO_4 Olivine

Numbers in meteorite type: petrologic classification (not mentioned in this lecture)
High type = more processed

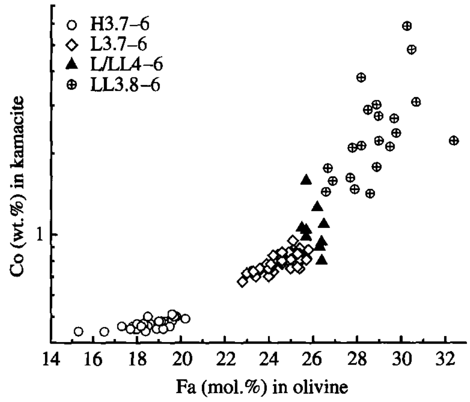


Figure 14 Fayalite (Fa) content (mol.%) in olivine versus Co content (wt.%) in FeNi-metal from ordinary chondrites (source Rubin, 1990).

Iron content and oxidation states

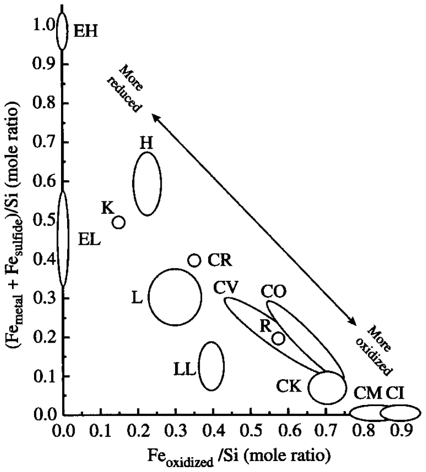


Figure 7 Urey–Craig diagram showing relative iron contents and oxidation states of the chondrite groups. Iron present in metal and sulfide phases is plotted versus iron present in silicate and oxide phases, for bulk chondrite compositions (after Brearley and Jones, 1998) (reproduced by permission of the Mineralogical Society of America from *Reviews in Mineralogy* **1998**, *36*, 1–398).

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{SMOW}} - 1 \right] \times 1{,}000$$

$$\delta^{17}O = \left[\frac{(^{17}O/^{16}O)_{sample}}{(^{17}O/^{16}O)_{SMOW}} - 1 \right] \times 1{,}000$$

SMOW = standard mean ocean water

TFL = terrestrial fractionation line according to evaporation from a liquid. Slope = 0.5 = (17-16)/(18-16)

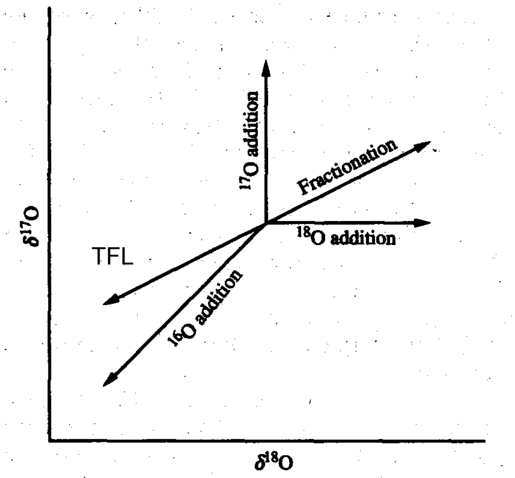
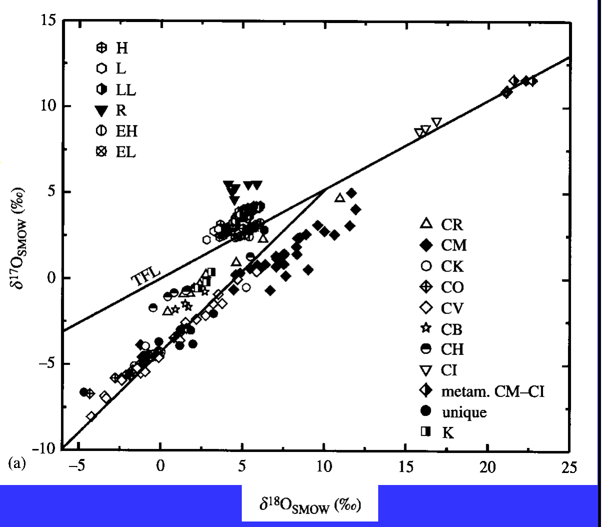
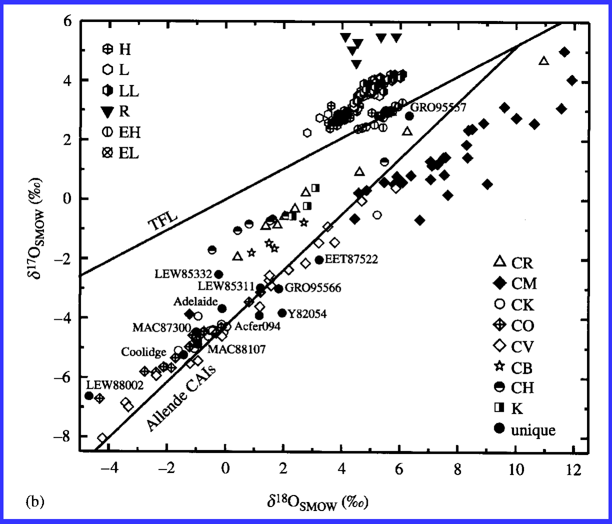


Figure 1 Schematic representation of various isotopic processes shown on an oxygen three-isotope plot. Almost all terrestrial materials plot along a line of "fractionation"; most primitive meteoritic materials plot near a line of "^{16}O addition."

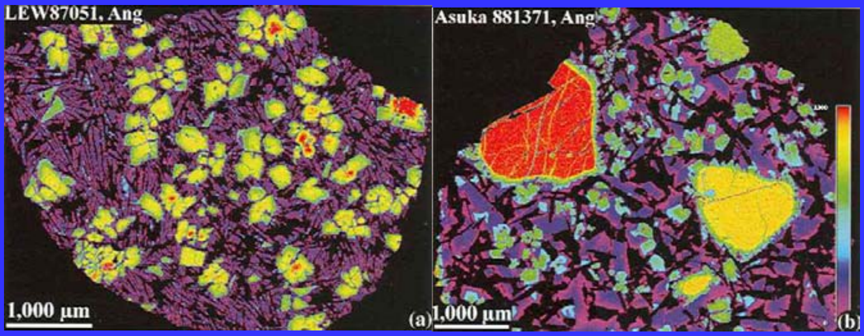
Slope of carbonaceous chondrites differs from TFL line and is close to line CCAM (carbonaceous chondrites anhydrous mineral) with exception of CI meteorites (they have hydrous minerals)



Same for ungrouped chondrites

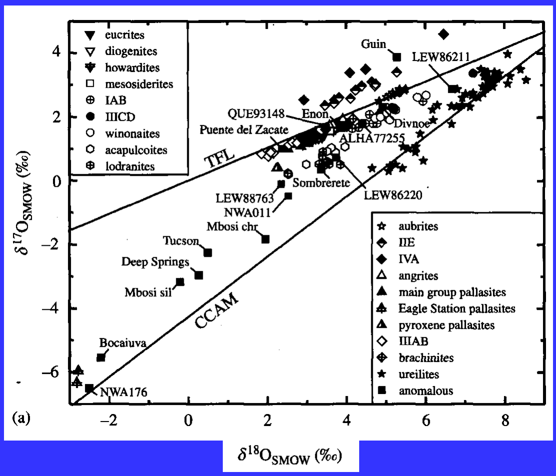


Differentiated Achondrites



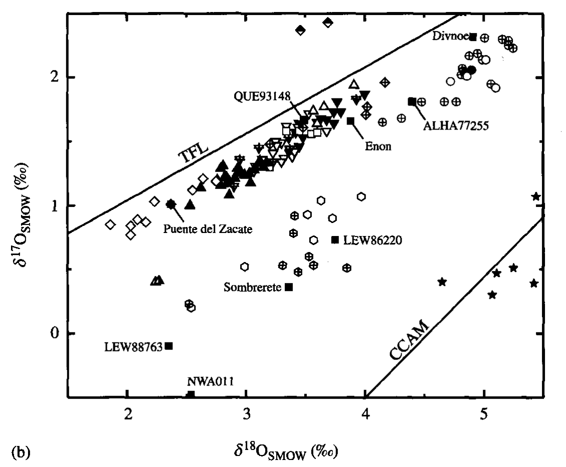
Angrites: medium- to coarse-grained (up to 2-3mm) igneous rocks of generally basaltic composition and consist mainly of Ca-Al-Ti-rich pyroxene, calcium-rich olivine and anorthitic plagioclase.
Yellow and red: subhedral to euhedral grains of magnesian olivine,
Purple: highly zoned Al-Ti diopside
Blue and green: ferroan olivine

Oxygen isotope diagrams of primitive achondrites



Some meteorites still follow CCAM line.

Oxygen isotope diagrams of differentiated meteorites



Mesosiderites

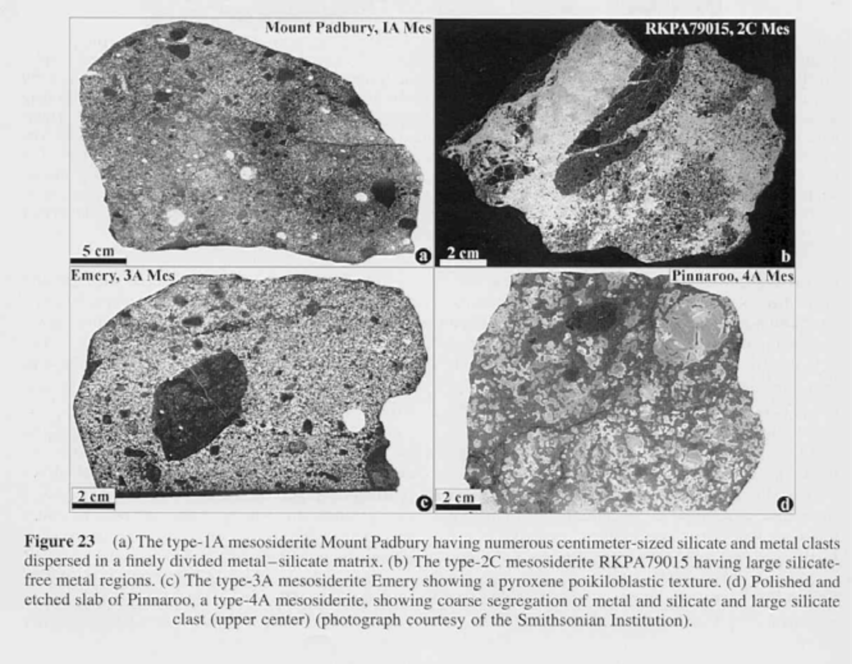
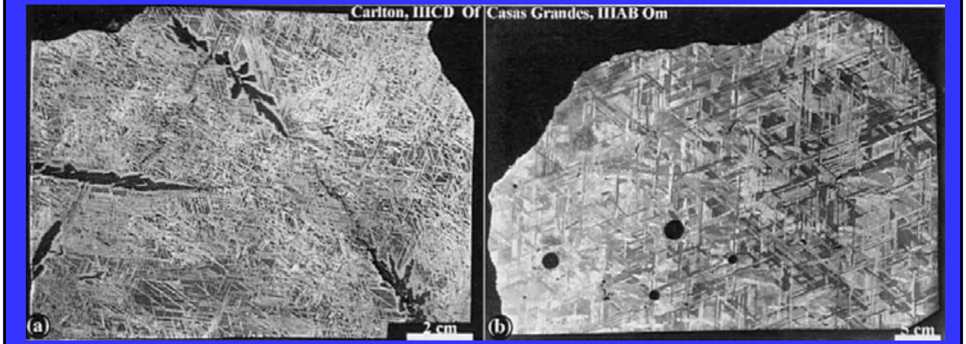
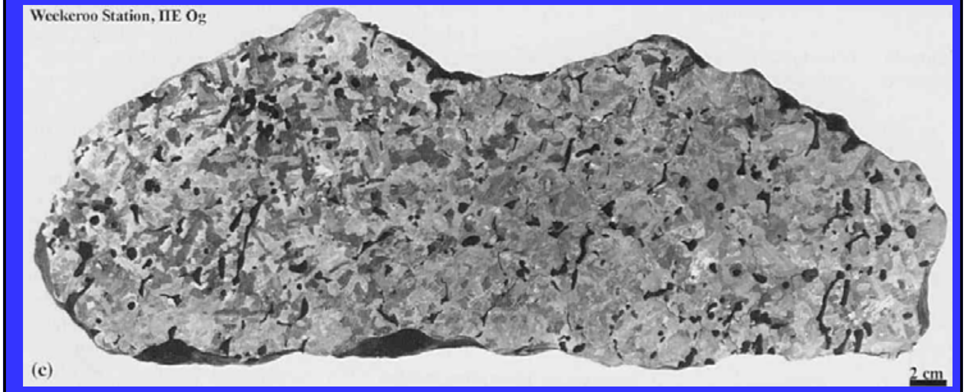


Figure 23 (a) The type-1A mesosiderite Mount Padbury having numerous centimeter-sized silicate and metal clasts dispersed in a finely divided metal–silicate matrix. (b) The type-2C mesosiderite RKPA79015 having large silicate-free metal regions. (c) The type-3A mesosiderite Emery showing a pyroxene poikiloblastic texture. (d) Polished and etched slab of Pinnaroo, a type-4A mesosiderite, showing coarse segregation of metal and silicate and large silicate clast (upper center) (photograph courtesy of the Smithsonian Institution).

Polished iron meteorites



Iron meteorites are thought to come from the interior of differentiated asteroids that were destroyed by collision



The coarse octahedrite IIE silicate bearing iron Wekeroo Station.
Silicate inclusions consist of plagioclase, orthopyroxene, and clinepyroxene.

Ages: Student talk by Esa Vilenius

$^{26}Al \rightarrow {}^{26}Mg$ half-life of 730,000 years.
^{26}Al is now extinct, but its daughter product ^{26}Mg has been found in chondrites.

^{26}Al may have contributed to early heating of meteorite parent bodies.

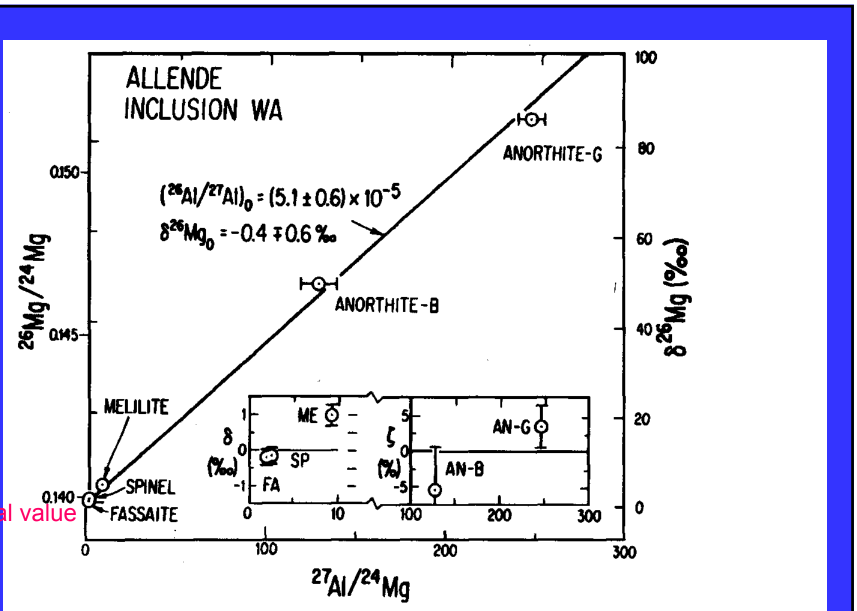
To find ^{26}Mg one must search for it in otherwise Mg-free minerals like anorthite.

$$^{26}\mathrm{Mg} = (^{26}\mathrm{Mg})_0 + (^{26}\mathrm{Mg})^{*} = (^{26}\mathrm{Mg})_0 + (^{26}\mathrm{Al})_0$$

$$\left(\frac{^{26}\mathrm{Mg}}{^{24}\mathrm{Mg}}\right) = \left(\frac{^{26}\mathrm{Mg}}{^{24}\mathrm{Mg}}\right)_0 + \left(\frac{^{26}\mathrm{Al}_0}{^{27}\mathrm{Al}}\right)\left(\frac{^{27}\mathrm{Al}}{^{24}\mathrm{Mg}}\right)$$

Such linear correlations are shown in the next viewgraphs.

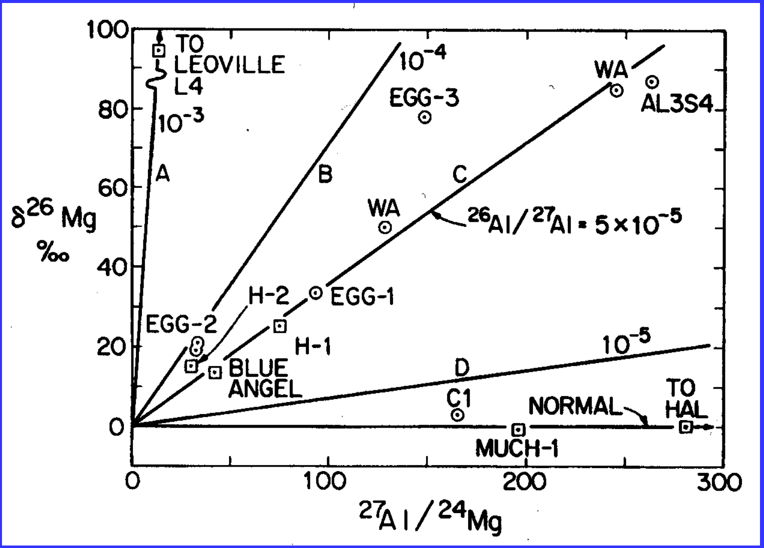
For Allende a value for the original ratio $^{26}Al/^{27}Al = 5 \times 10^{-5}$ has been found.
This indicates that part of the ^{26}Al to be expected from nuclide generation had already decayed before implementation in the meteorite.



terrestrial value

Figure 8.13. ^{26}Al in Allende. Deviations of the data from the line fit are shown in the inset. From Wasserburg and Papanastassiou (1982) with permission.

Plots of measurements made in different meteorites shows a spread in slope, i.e. a spread in the fractions $^{26}Al/^{27}Al$ at implementation into the meteorite.



Origin of chondrules and CAIs

Concerning the origin of chondrules and CAIs modern theories relay on transport of the chondrules and CAIs in the protosolar disk.

Work by *Shu et al.*:
The origin of chondrules and refractory inclusions in chondritic meteorites,
Ap. J. 548, 1029-1050, 2001

Toward an astrophysical theory of chondrites, Science 271, 1545-1551, 1996

X-rays and fluctuating x-winds from protostars, Science 277, 1475-1479, 1997

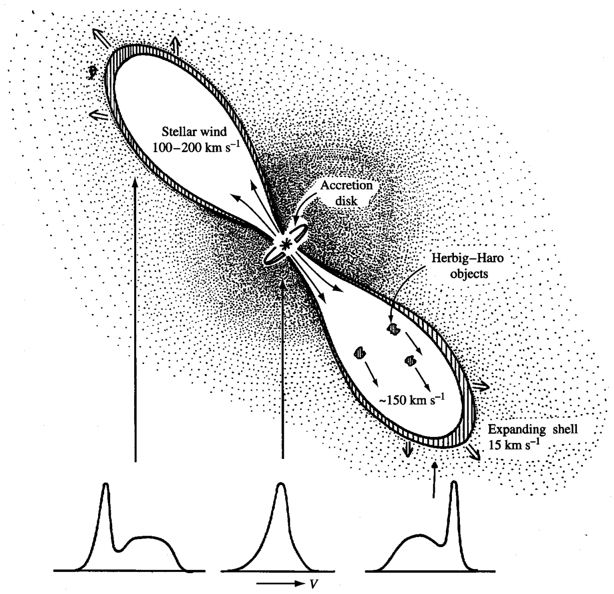
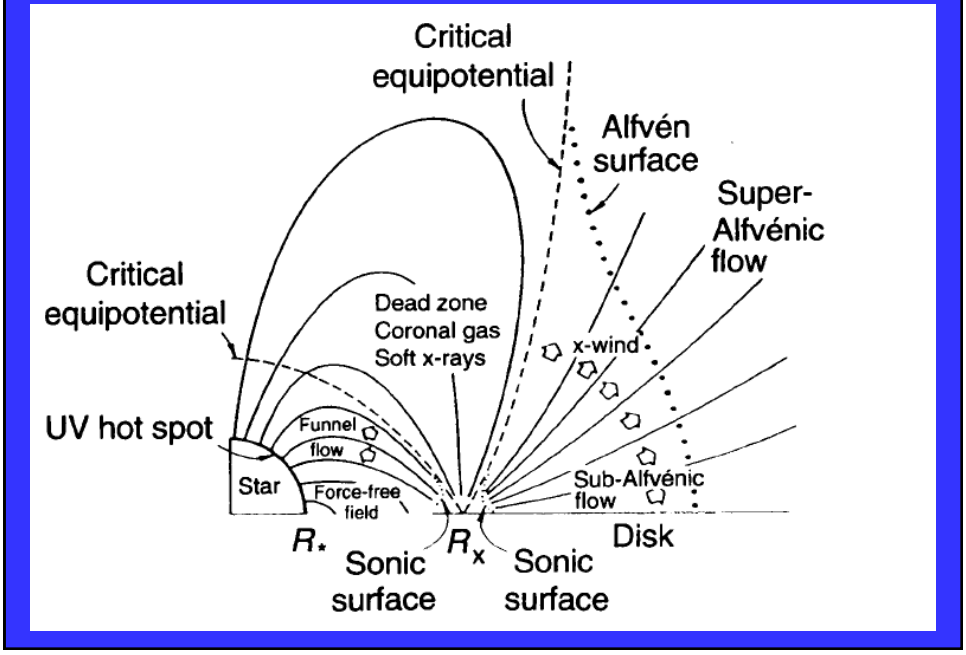


Figure 3 The prototypical young star with a bipolar outflow, L1551 IRS5 (Snell *et al.*, 1980), now known to harbor a binary protostar, with a separation of 45 AU, and where each protostar is orbited by a disk with a radius of ~10 AU and a mass of ~0.05 solar masses (Snell *et al.*, 1980) (reproduced by permission of University of Chicago Press and American Astronomical Society from *Astrophys. J.*, **1980**, *239*, L17–L22).

The X-wind model



Motion of grains in the X-wind