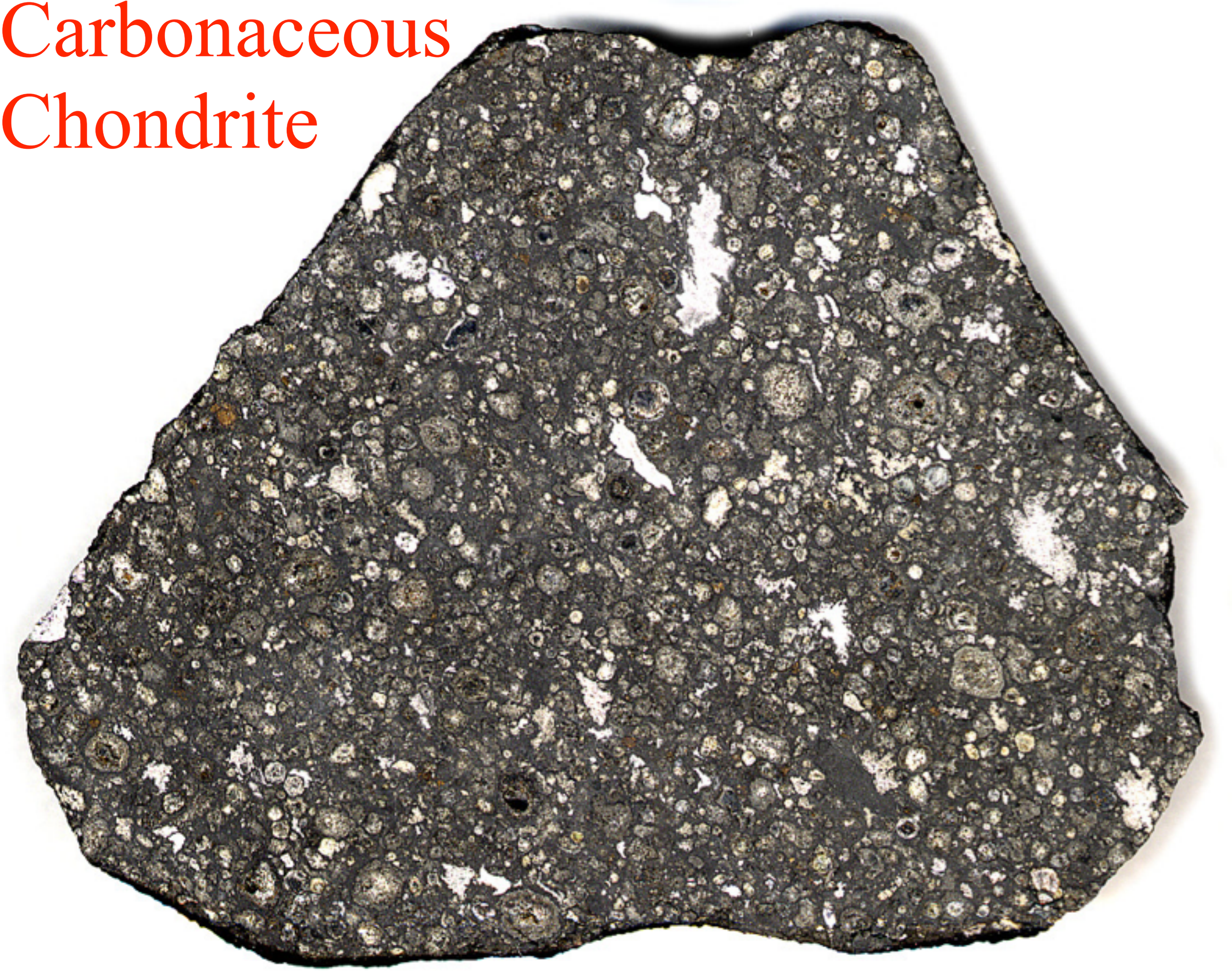
Chapter 11: Meteorites

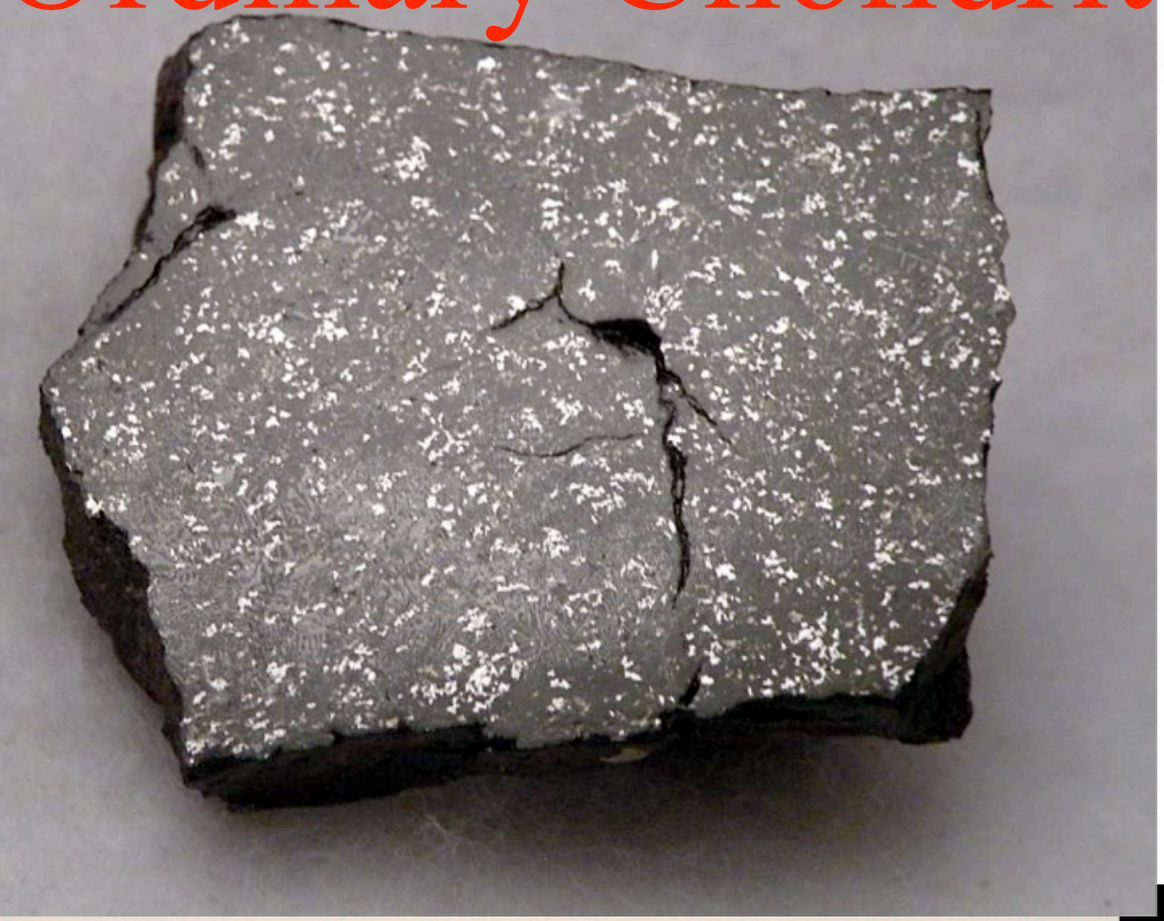
Topics:

Meteorite Types
Radioactive Heating
Radioactive Dating

Carbonaceous Chondrite



Ordinary Chondrites



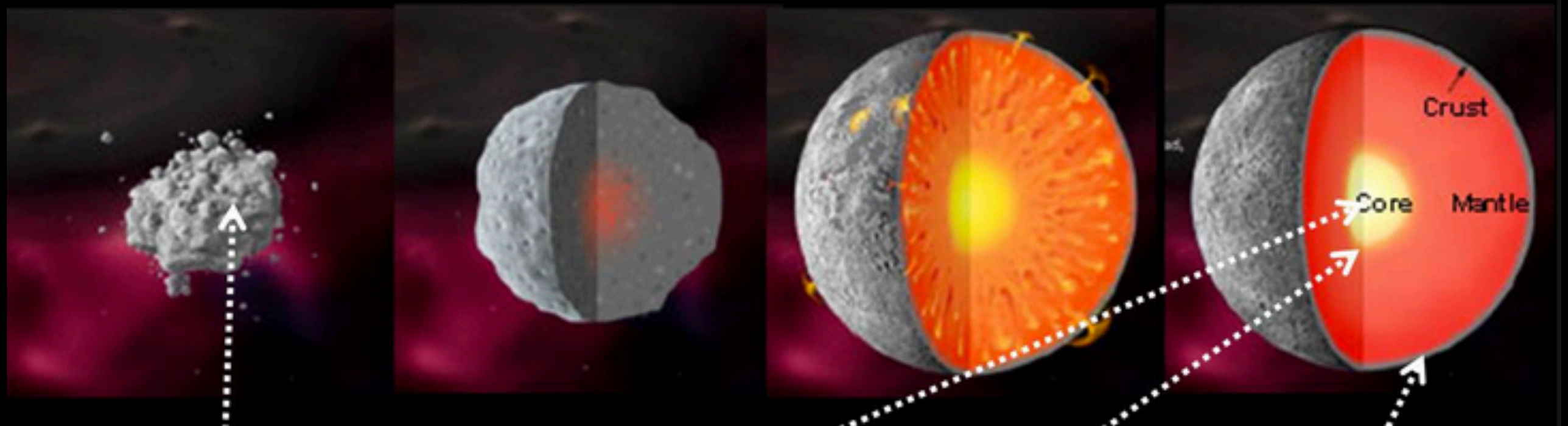
Achondrites

Pallasites (Stony-Iron)

Iron Meteorites

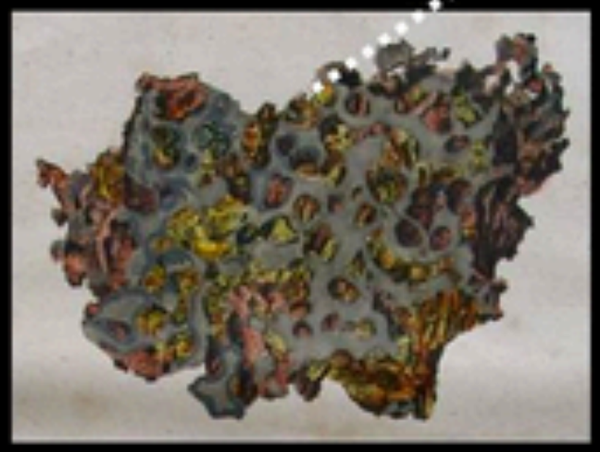
Different Asteroid & Meteorite Types

Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html



Chondritic Stony Meteorite

Iron Meteorite



Pallasite Meteorite

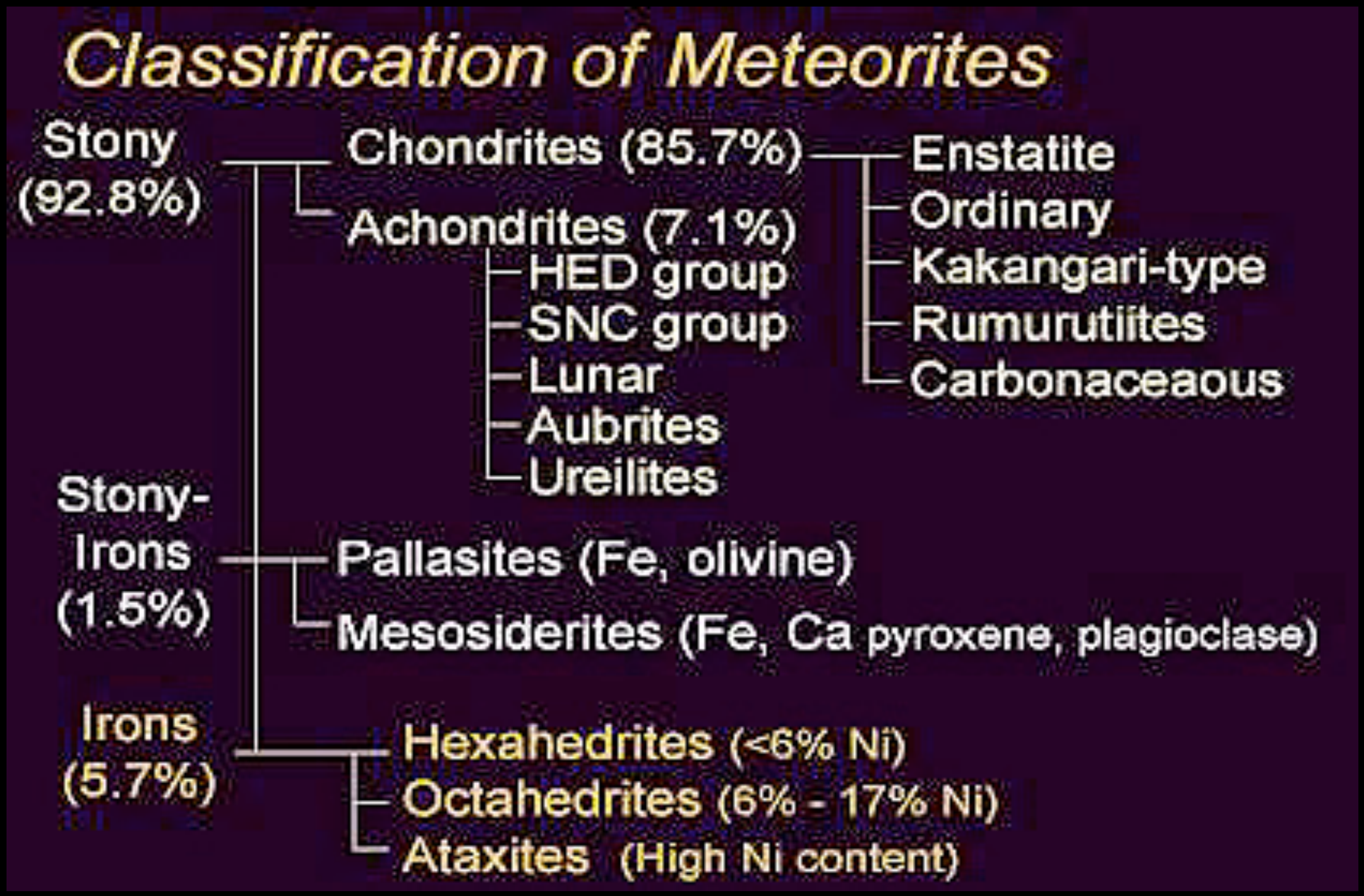
Achondritic Stony Meteorite

Asteroid Type C

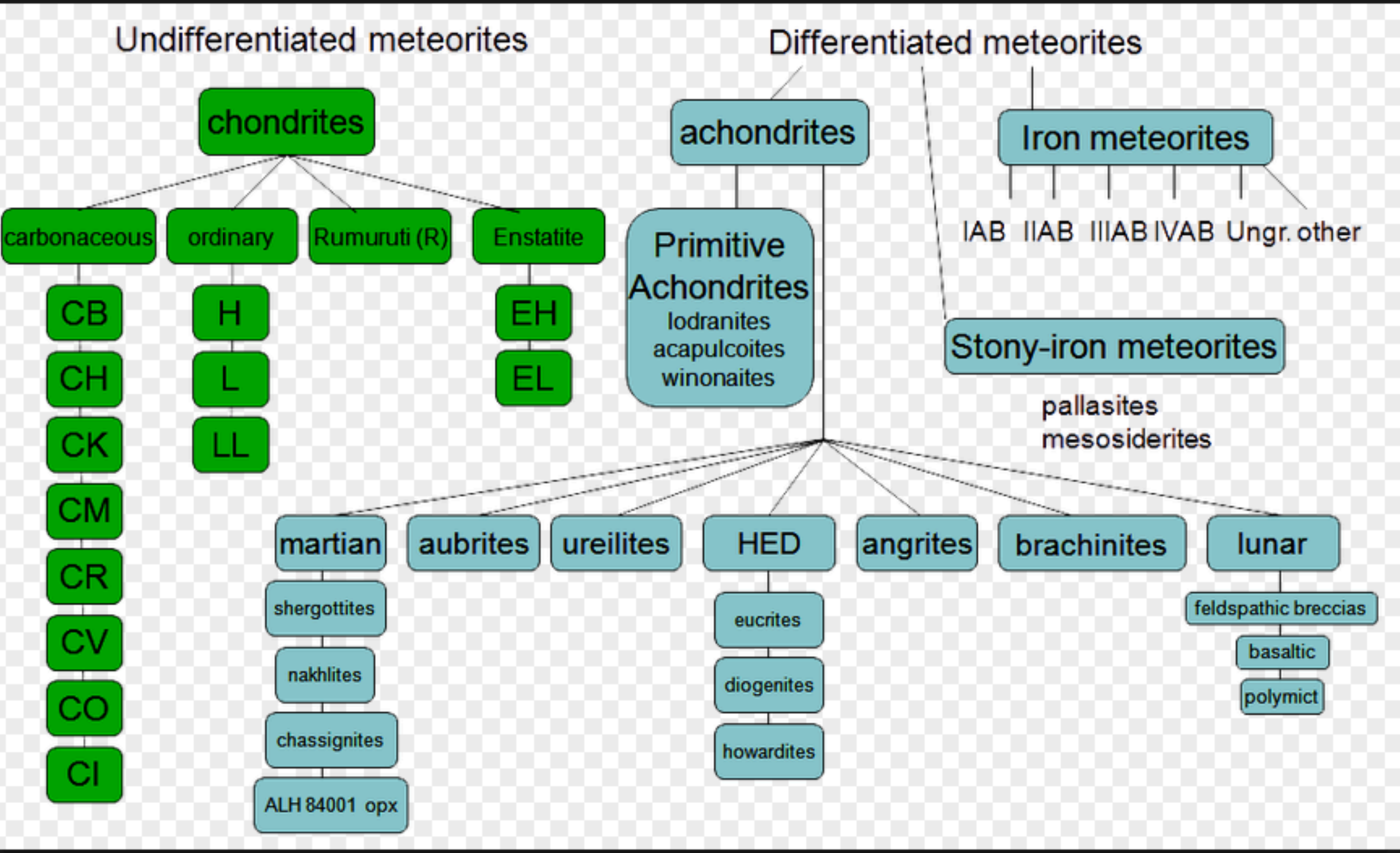
Asteroid Type M

Asteroid Type S

Classification: Intermediate Guide



Classification: Advanced Guide



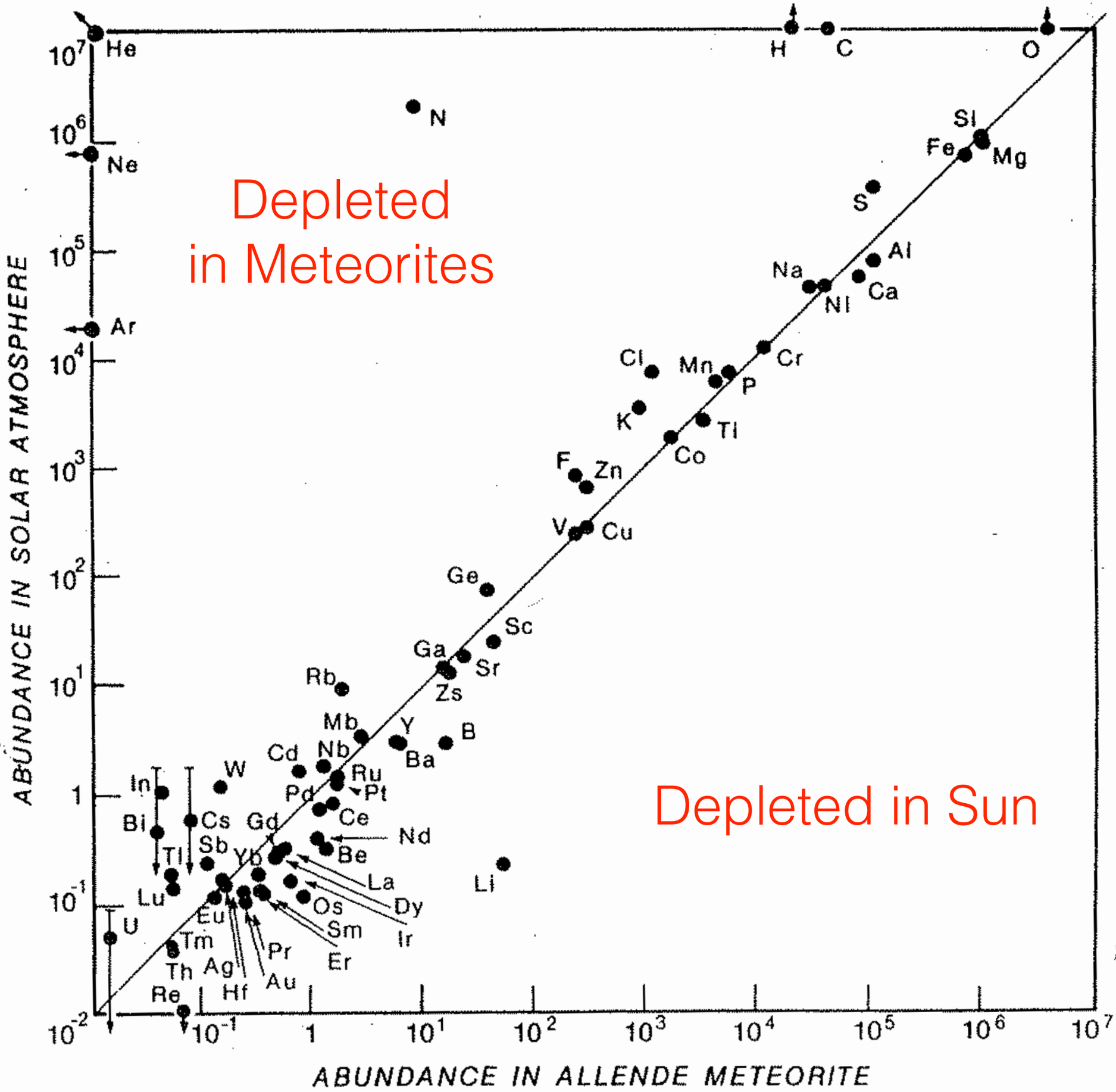


Figure 8.2 The abundance
ments in the Sun's photosph
ted against their abundanc
Allende CV3 chondrite. M
ments lie very close to th
of equal abundance (norm
silicon). Several volatile e
lie above this curve, pre
because they are depleted
orites (rather than being en
the Sun), while only lithium
stantially below the curve; l
depleted in the solar phot
because it is destroyed by
reactions near the base of t
convective zone.

TABLE 8.3 Half-lives of Selected Isotopes.

Parent	Measurable stable daughter(s)	Half-life $t_{1/2}$
Long-lived radionuclides		
^{40}K	^{40}Ar, ^{40}Ca	1.25 Gyr
^{87}Rb (Rubidium)	^{87}Sr (Strontium)	48.8 Gyr
^{147}Sm	^{143}Nd, ^{4}He	106 Gyr
^{187}Re	^{187}Os	46 Gyr
^{232}Th	^{208}Pb, ^{4}He	14 Gyr
^{235}U	^{207}Pb, ^{4}He	0.704 Gyr
^{238}U	^{206}Pb, ^{4}He	4.47 Gyr
Extinct radionuclides		
^{22}Na	^{22}Ne	2.6 yr
^{26}Al	^{26}Mg	0.72 Myr
^{41}Ca	^{41}K	0.1 Myr
^{53}Mn	^{53}Cr	3.6 Myr
^{60}Fe	^{60}Ni	1.5 Myr
^{107}Pd	^{107}Ag	6.5 Myr
^{129}I	^{129}Xe	17 Myr
^{182}Hf	^{182}W	9 Myr
^{244}Pu	$^{131-136}Xe$	82 Myr

Important for heating

$$
{}^{238}_{92}\mathrm{U} \xrightarrow[t_{1/2}=4.51\times10^{9}\mathrm{y}]{\alpha} {}^{234}_{90}\mathrm{Th} \xrightarrow[21.4\mathrm{d}]{\beta} {}^{234}_{91}\mathrm{Pa} \xrightarrow[6.75\mathrm{h}]{\beta} {}^{234}_{92}\mathrm{U}
$$

$$
\xrightarrow[2.47\times10^{5}\mathrm{y}]{\alpha} {}^{230}_{90}\mathrm{Th} \xrightarrow[8\times10^{4}\mathrm{y}]{\alpha} {}^{226}_{88}\mathrm{Ra} \xrightarrow[1600\mathrm{y}]{\alpha} {}^{222}_{86}\mathrm{Rn}
$$ (Radon)

$$
\xrightarrow[3.8\mathrm{d}]{\alpha} {}^{218}_{84}\mathrm{Po} \xrightarrow[3\mathrm{m}]{\alpha} {}^{214}_{82}\mathrm{Pb} \xrightarrow[27\mathrm{m}]{\beta} {}^{214}_{83}\mathrm{Bi} \xrightarrow[19.7\mathrm{m}]{\beta} {}^{214}_{84}\mathrm{Po}
$$

$$
\xrightarrow[1.64\times10^{-4}\mathrm{s}]{\alpha} {}^{210}_{82}\mathrm{Pb} \xrightarrow[21\mathrm{y}]{\beta} {}^{210}_{83}\mathrm{Bi} \xrightarrow[5\mathrm{d}]{\beta} {}^{210}_{84}\mathrm{Po} \xrightarrow[183\mathrm{d}]{\alpha} {}^{206}_{82}\mathrm{Pb}\ \text{(stable)},
$$

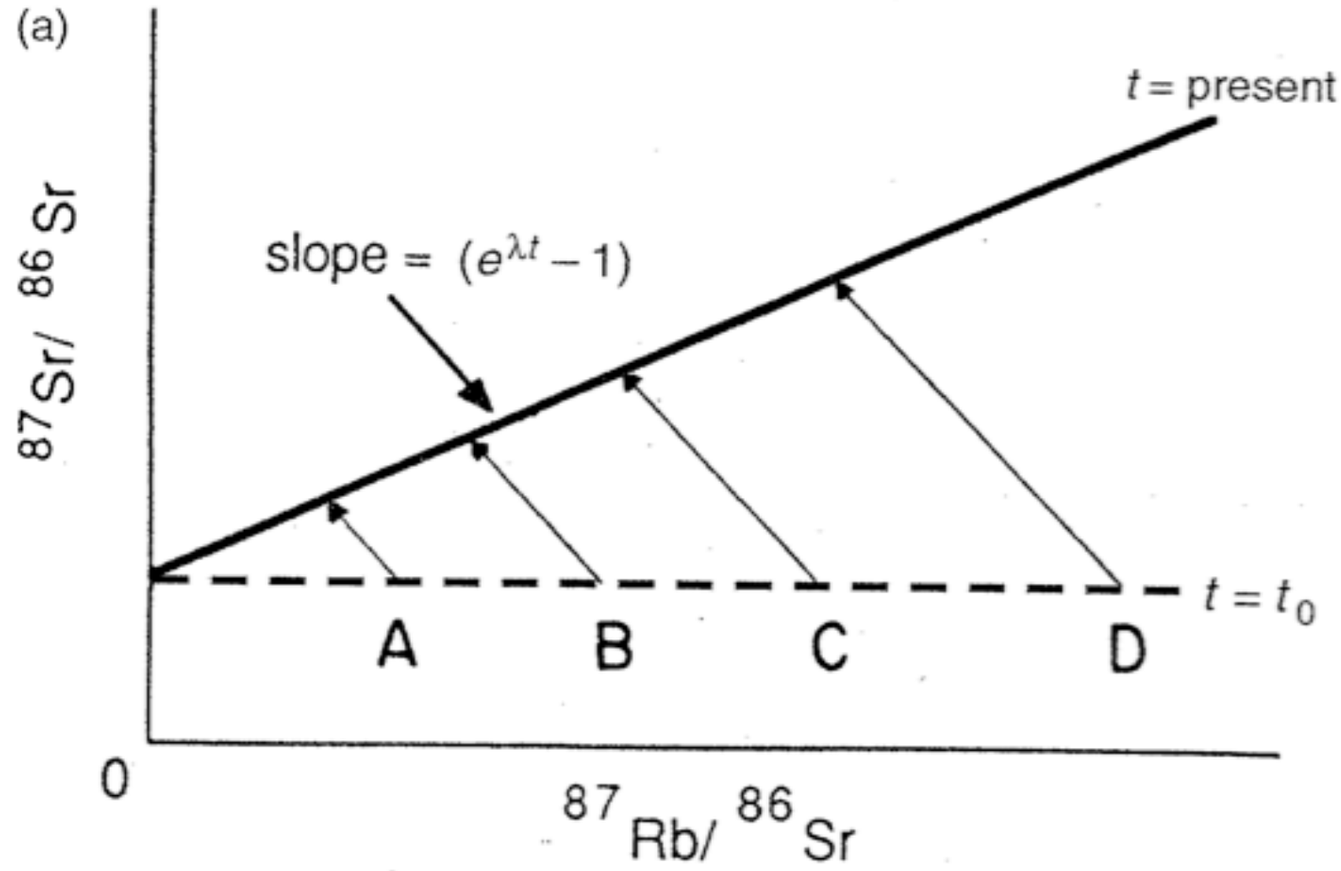
$$
{}^{235}_{92}\mathrm{U} \xrightarrow[t_{1/2}=7.1\times10^{8}\mathrm{y}]{\alpha} {}^{231}_{90}\mathrm{Th} \xrightarrow[25.5\mathrm{h}]{\beta} {}^{231}_{91}\mathrm{Pa} \xrightarrow[3.25\times10^{4}\mathrm{y}]{\alpha} {}^{227}_{89}\mathrm{Ac}
$$

$$
\xrightarrow[21.6\mathrm{y}]{\beta} {}^{227}_{90}\mathrm{Th} \xrightarrow[18.5\mathrm{d}]{\alpha} {}^{223}_{88}\mathrm{Ra} \xrightarrow[11.43\mathrm{d}]{\alpha} {}^{219}_{86}\mathrm{Rn} \xrightarrow[4\mathrm{s}]{\alpha} {}^{215}_{84}\mathrm{Po}
$$

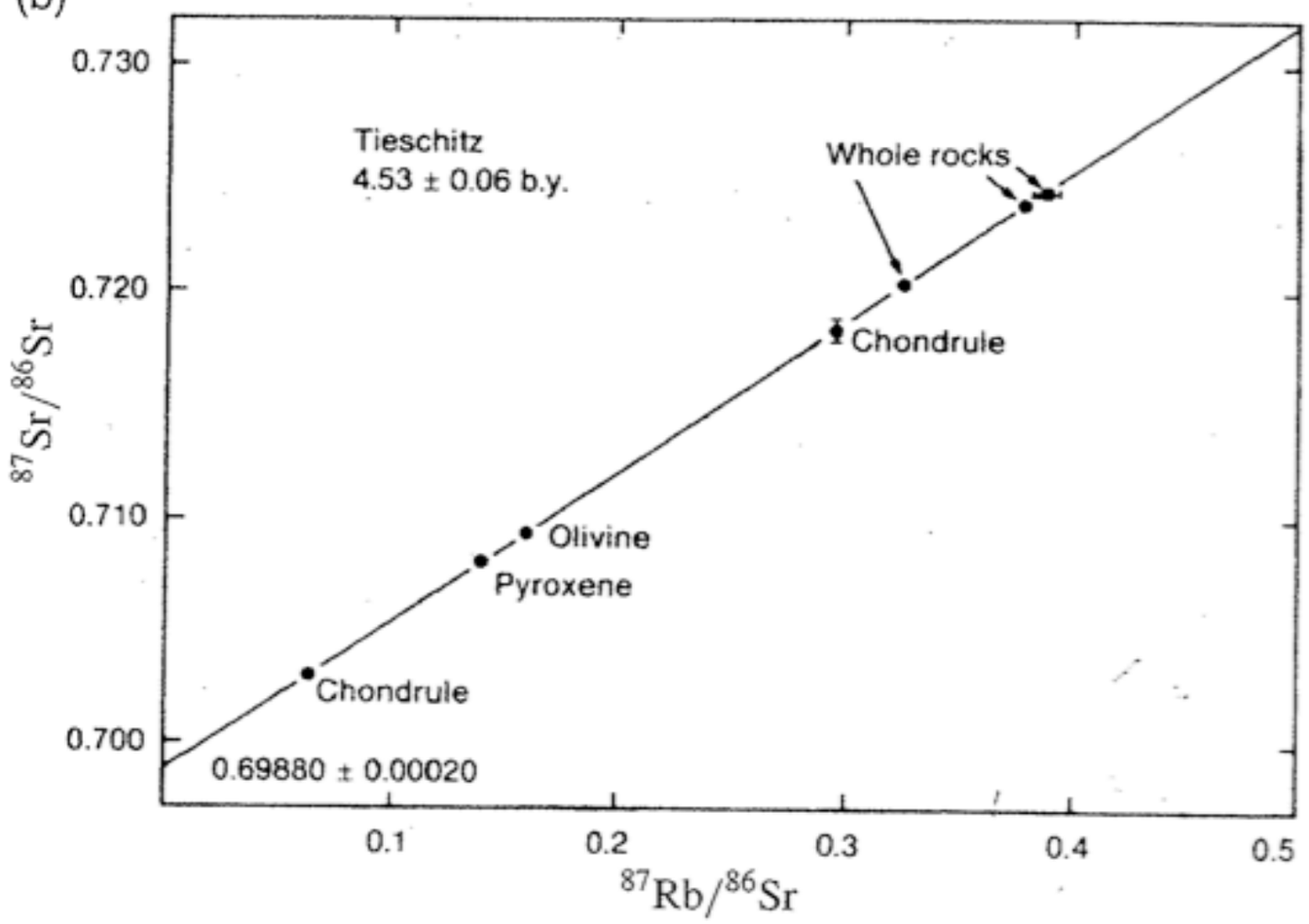
$$
\xrightarrow[1.8\times10^{-3}\mathrm{s}]{\alpha} {}^{211}_{82}\mathrm{Pb} \xrightarrow[36\mathrm{m}]{\beta} {}^{211}_{83}\mathrm{Bi} \xrightarrow[2.15\mathrm{m}]{\alpha} {}^{207}_{81}\mathrm{Tl}
$$

$$
\xrightarrow[4.8\mathrm{m}]{\beta} {}^{207}_{82}\mathrm{Pb}\ \text{(stable)}. \qquad (8.6b)
$$

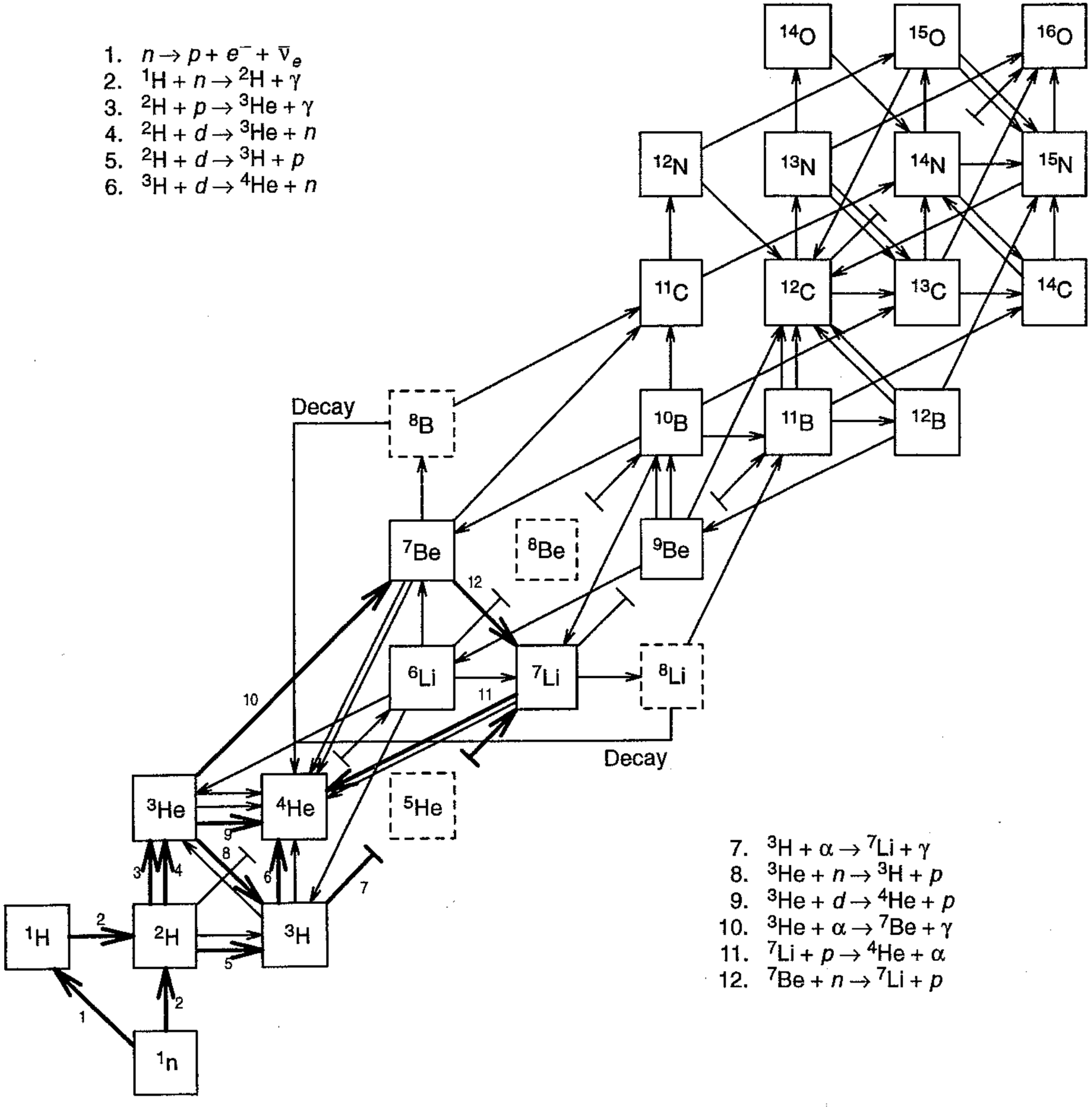
(a)


t = present
slope = $(e^{\lambda t} - 1)$
$^{87}Sr/^{86}Sr$
t = t_0
A
B
C
D
0
$^{87}Rb/^{86}Sr$

(b)


0.730
0.720
0.710
0.700
Tieschitz
4.53 ± 0.06 b.y.
Whole rocks
Chondrule
Olivine
Pyroxene
Chondrule
0.69880 ± 0.00020
0.1
0.2
0.3
0.4
0.5
$^{87}Sr/^{86}Sr$
$^{87}Rb/^{86}Sr$

1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $^1H + n \rightarrow {}^2H + \gamma$
3. $^2H + p \rightarrow {}^3He + \gamma$
4. $^2H + d \rightarrow {}^3He + n$
5. $^2H + d \rightarrow {}^3H + p$
6. $^3H + d \rightarrow {}^4He + n$



7. $^3H + \alpha \rightarrow {}^7Li + \gamma$
8. $^3He + n \rightarrow {}^3H + p$
9. $^3He + d \rightarrow {}^4He + p$
10. $^3He + \alpha \rightarrow {}^7Be + \gamma$
11. $^7Li + p \rightarrow {}^4He + \alpha$
12. $^7Be + n \rightarrow {}^7Li + p$

PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

PERIOD	1 IA												13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 **H** HYDROGEN	2 IIA																2 4.0026 **He** HELIUM
2	3 6.941 **Li** LITHIUM	4 9.0122 **Be** BERYLLIUM											5 10.811 **B** BORON	6 12.011 **C** CARBON	7 14.007 **N** NITROGEN	8 15.999 **O** OXYGEN	9 18.998 **F** FLUORINE	10 20.180 **Ne** NEON
3	11 22.990 **Na** SODIUM	12 24.305 **Mg** MAGNESIUM	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 26.982 **Al** ALUMINIUM	14 28.086 **Si** SILICON	15 30.974 **P** PHOSPHORUS	16 32.065 **S** SULPHUR	17 35.453 **Cl** CHLORINE	18 39.948 **Ar** ARGON
4	19 39.098 **K** POTASSIUM	20 40.078 **Ca** CALCIUM	21 44.956 **Sc** SCANDIUM	22 47.867 **Ti** TITANIUM	23 50.942 **V** VANADIUM	24 51.996 **Cr** CHROMIUM	25 54.938 **Mn** MANGANESE	26 55.845 **Fe** IRON	27 58.933 **Co** COBALT	28 58.693 **Ni** NICKEL	29 63.546 **Cu** COPPER	30 65.39 **Zn** ZINC	31 69.723 **Ga** GALLIUM	32 72.64 **Ge** GERMANIUM	33 74.922 **As** ARSENIC	34 78.96 **Se** SELENIUM	35 79.904 **Br** BROMINE	36 83.80 **Kr** KRYPTON
5	37 85.468 **Rb** RUBIDIUM	38 87.62 **Sr** STRONTIUM	39 88.906 **Y** YTTRIUM	40 91.224 **Zr** ZIRCONIUM	41 92.906 **Nb** NIOBIUM	42 95.94 **Mo** MOLYBDENUM	43 (98) **Tc** TECHNETIUM	44 101.07 **Ru** RUTHENIUM	45 102.91 **Rh** RHODIUM	46 106.42 **Pd** PALLADIUM	47 107.87 **Ag** SILVER	48 112.41 **Cd** CADMIUM	49 114.82 **In** INDIUM	50 118.71 **Sn** TIN	51 121.76 **Sb** ANTIMONY	52 127.60 **Te** TELLURIUM	53 126.90 **I** IODINE	54 131.29 **Xe** XENON
6	55 132.91 **Cs** CAESIUM	56 137.33 **Ba** BARIUM	57-71 **La-Lu** Lanthanide	72 178.49 **Hf** HAFNIUM	73 180.95 **Ta** TANTALUM	74 183.84 **W** TUNGSTEN	75 186.21 **Re** RHENIUM	76 190.23 **Os** OSMIUM	77 192.22 **Ir** IRIDIUM	78 195.08 **Pt** PLATINUM	79 196.97 **Au** GOLD	80 200.59 **Hg** MERCURY	81 204.38 **Tl** THALLIUM	82 207.2 **Pb** LEAD	83 208.98 **Bi** BISMUTH	84 (209) **Po** POLONIUM	85 (210) **At** ASTATINE	86 (222) **Rn** RADON
7	87 (223) **Fr** FRANCIUM	88 (226) **Ra** RADIUM	89-103 **Ac-Lr** Actinide	104 (261) **Rf** RUTHERFORDIUM	105 (262) **Db** DUBNIUM	106 (266) **Sg** SEABORGIUM	107 (264) **Bh** BOHRIUM	108 (277) **Hs** HASSIUM	109 (268) **Mt** MEITNERIUM	110 (281) **Uun** UNUNNILIUM	111 (272) **Uuu** UNUNUNIUM	112 (285) **Uub** UNUNBIUM		114 (289) **Uuq** UNUNQUADIUM				

GROUP

PERIOD

RELATIVE ATOMIC MASS (1)

GROUP IUPAC

GROUP CAS

ATOMIC NUMBER

SYMBOL

ELEMENT NAME

Metal · Semimetal · Nonmetal

1 Alkali metal

2 Alkaline earth metal

Transition metals

Lanthanide

Actinide

16 Chalcogens element

17 Halogens element

18 Noble gas

STANDARD STATE (25 °C; 101 kPa)

Ne - gas · Fe - solid

Ga - liquid · Tc - synthetic

LANTHANIDE

57 138.91 **La** LANTHANUM	58 140.12 **Ce** CERIUM	59 140.91 **Pr** PRASEODYMIUM	60 144.24 **Nd** NEODYMIUM	61 (145) **Pm** PROMETHIUM	62 150.36 **Sm** SAMARIUM	63 151.96 **Eu** EUROPIUM	64 157.25 **Gd** GADOLINIUM	65 158.93 **Tb** TERBIUM	66 162.50 **Dy** DYSPROSIUM	67 164.93 **Ho** HOLMIUM	68 167.26 **Er** ERBIUM	69 168.93 **Tm** THULIUM	70 173.04 **Yb** YTTERBIUM	71 174.97 **Lu** LUTETIUM

ACTINIDE

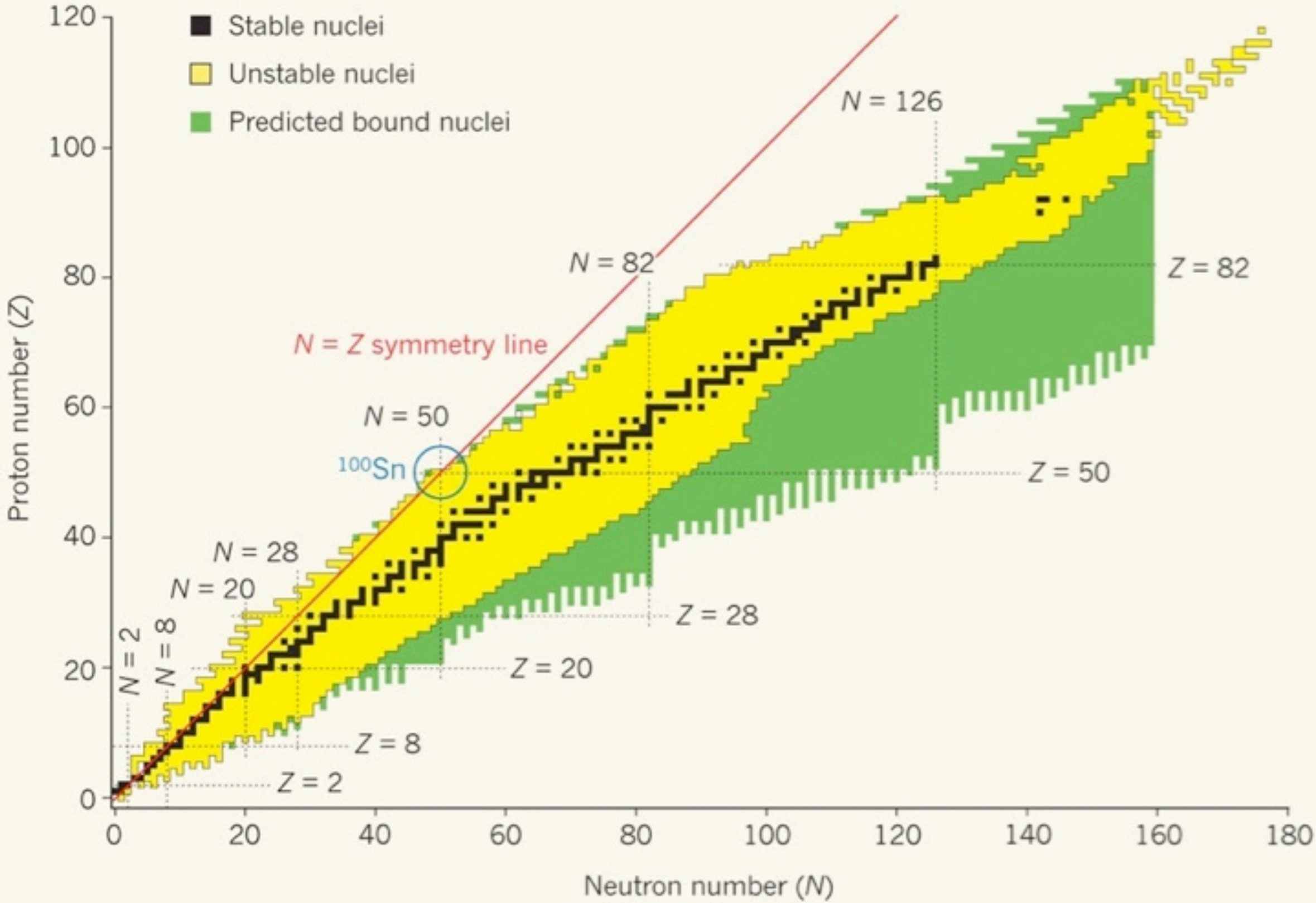
89 (227) **Ac** ACTINIUM	90 232.04 **Th** THORIUM	91 231.04 **Pa** PROTACTINIUM	92 238.03 **U** URANIUM	93 (237) **Np** NEPTUNIUM	94 (244) **Pu** PLUTONIUM	95 (243) **Am** AMERICIUM	96 (247) **Cm** CURIUM	97 (247) **Bk** BERKELIUM	98 (251) **Cf** CALIFORNIUM	99 (252) **Es** EINSTEINIUM	100 (257) **Fm** FERMIUM	101 (258) **Md** MENDELEVIUM	102 (259) **No** NOBELIUM	103 (262) **Lr** LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

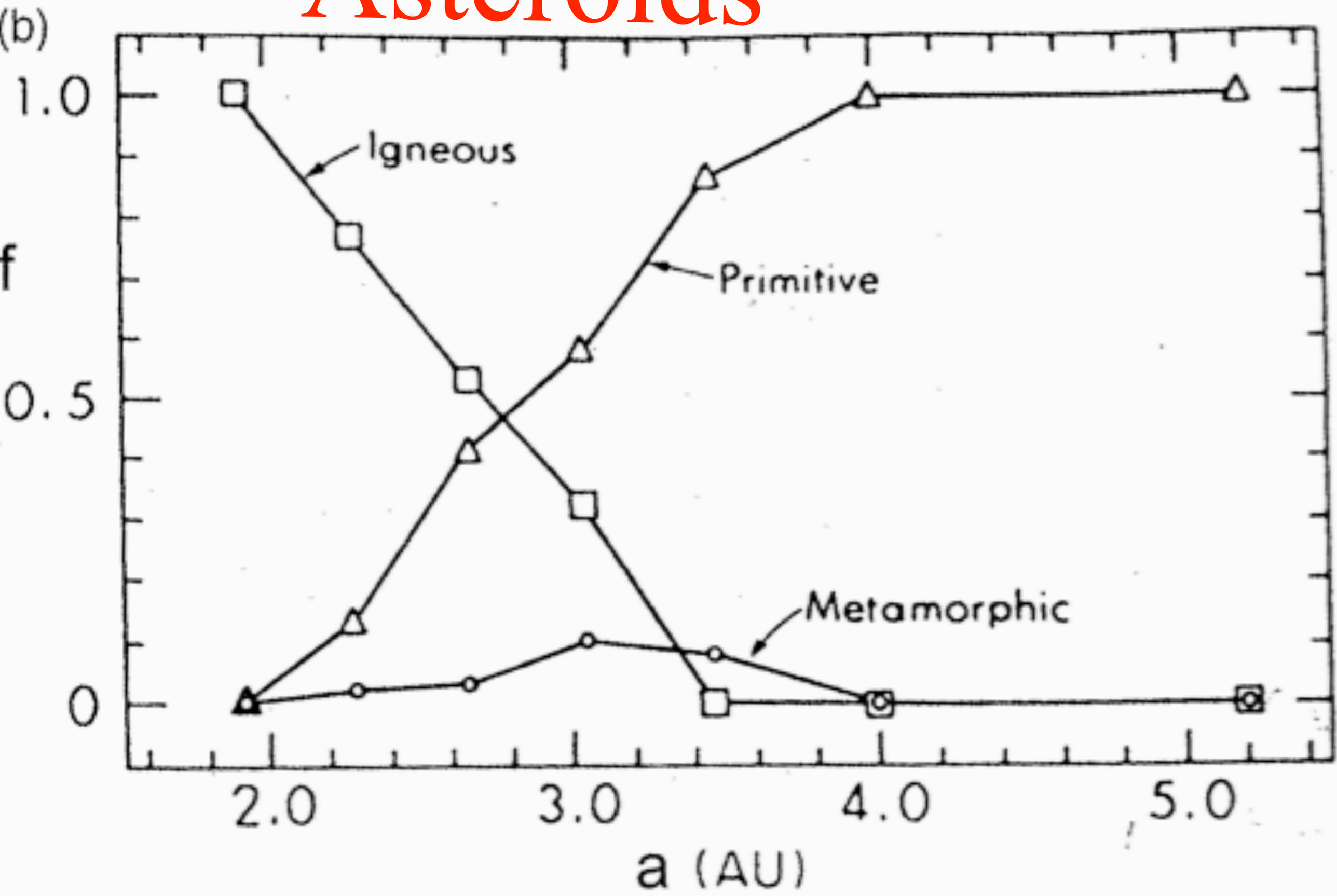
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

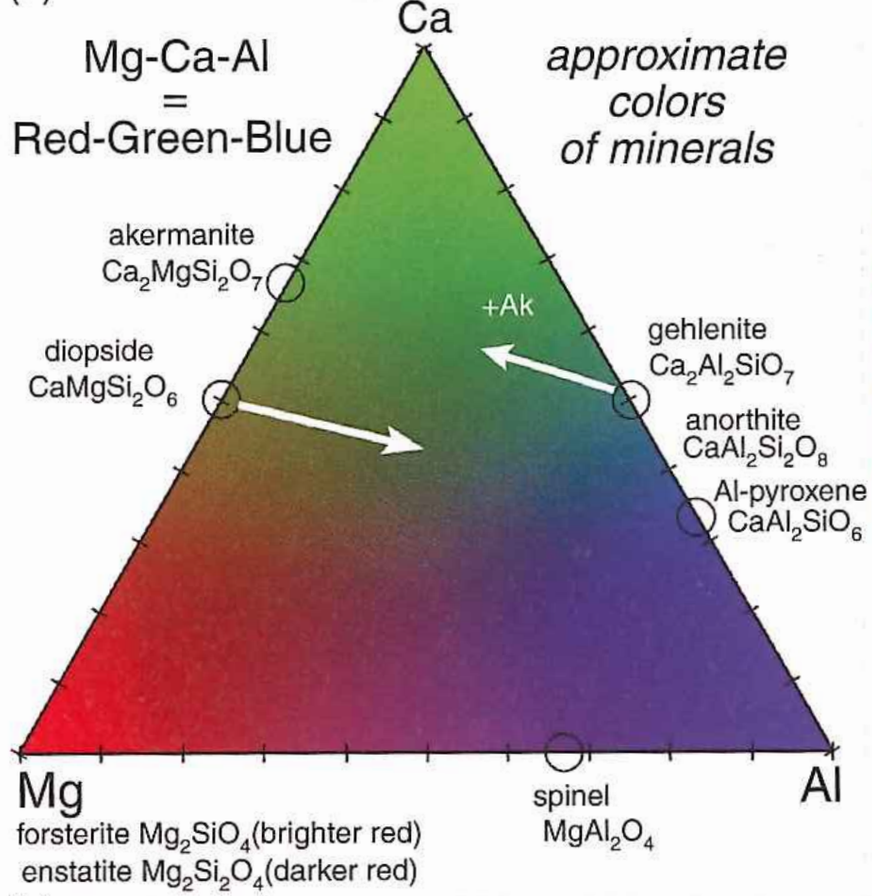
Editor: Aditya Vardhan (adivar@netlinx.com)

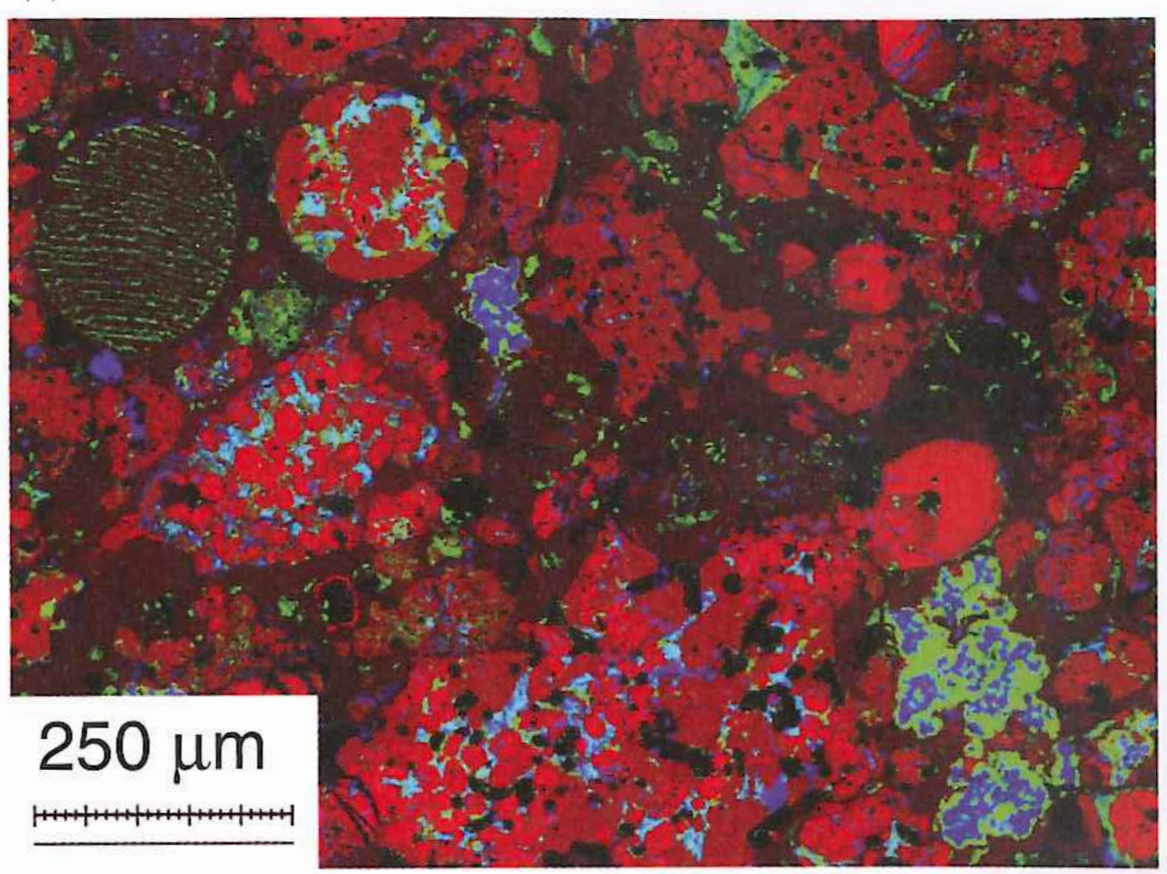

Stable nuclei
Unstable nuclei
Predicted bound nuclei
N = 126
N = 82
Z = 82
N = Z symmetry line
N = 50
100Sn
Z = 50
N = 28
N = 20
Z = 28
N = 2
N = 8
Z = 20
Z = 8
Z = 2
Proton number (Z)
Neutron number (N)
0
20
40
60
80
100
120
140
160
180

Element		Solar System[b] (atoms/10^6 Si)	CI chondrites (mass fraction)	Element		Solar System[b] (atoms/10^6 Si)	CI chondrites (mass fraction)
1	H	2.431×10^{10}	21.0 mg/g	44	Ru	1.90	692 ng/g
2	He	2.343×10^{9}	56 nL/g	45	Rh	0.37	141 ng/g
3	Li	55.5	1.46 μg/g	46	Pd	1.44	588 ng/g
4	Be	0.74	25.2 ng/g	47	Ag	0.49	201 ng/g
5	B	17.3	713 ng/g	48	Cd	1.58	675 ng/g
6	C	7.08×10^{6}	35.2 mg/g	49	In	0.18	78.8 ng/g
7	N	1.95×10^{6}	2.94 mg/g	50	Sn	3.73	1.68 μg/g
8	O	1.41×10^{7}	458.2 mg/g	51	Sb	0.33	152 ng/g
9	F	841	60.6 μg/g	52	Te	4.82	2.33 μg/g
10	Ne	2.15×10^{6}	218 pL/g	53	I	1.00	480 ng/g
11	Na	5.75×10^{4}	5.01 mg/g	54	Xe	5.39	31.3 pL/g
12	Mg	1.02×10^{6}	95.9 mg/g	55	Cs	0.37	185 ng/g
13	Al	8.41×10^{4}	8.50 mg/g	56	Ba	4.35	2.31 μg/g
14	Si	1.00×10^{6}	106.5 mg/g	57	La	0.44	232 ng/g
15	P	8370	920 μg/g	58	Ce	1.17	621 ng/g
16	S	4.45×10^{5}	54.1 mg/g	59	Pr	0.17	92.8 ng/g
17	Cl	5240	704 μg/g	60	Nd	0.84	457 ng/g
18	Ar	1.03×10^{5}	888 pL/g	62	Sm	0.25	145 ng/g
19	K	3690	530 μg/g	63	Eu	0.095	54.6 ng/g
20	Ca	6.29×10^{4}	9.07 mg/g	64	Gd	0.33	198 ng/g
21	Sc	34.2	5.83 μg/g	65	Tb	0.059	35.6 ng/g
22	Ti	2420	440 μg/g	66	Dy	0.39	238 ng/g
23	V	288	55.7 μg/g	67	Ho	0.090	56.2 ng/g
24	Cr	1.29×10^{4}	2.59 mg/g	68	Er	0.26	162 ng/g
25	Mn	9170	1.91 mg/g	69	Tm	0.036	23.7 ng/g
26	Fe	8.38×10^{5}	182.8 mg/g	70	Yb	0.25	163 ng/g
27	Co	2320	502 μg/g	71	Lu	0.037	23.7 ng/g
28	Ni	4.78×10^{4}	10.6 mg/g	72	Hf	0.17	115 ng/g
29	Cu	527	127 μg/g	73	Ta	0.021	14.4 ng/g
30	Zn	1230	310 μg/g	74	W	0.13	89 ng/g
31	Ga	36.0	9.51 μg/g	75	Re	0.053	37 ng/g
32	Ge	121	33.2 μg/g	76	Os	0.67	486 ng/g
33	As	6.09	1.73 μg/g	77	Ir	0.64	470 ng/g
34	Se	65.8	19.7 μg/g	78	Pt	1.36	1.00 μg/g
35	Br	11.3	3.43 μg/g	79	Au	0.20	146 ng/g
36	Kr	55.2	15.3 pL/g	80	Hg	0.41	314 ng/g
37	Rb	6.57	2.13 μg/g	81	Tl	0.18	143 ng/g
38	Sr	23.6	7.74 μg/g	82	Pb	3.26	2.56 μg/g
39	Y	4.61	1.53 μg/g	83	Bi	0.14	110 ng/g
40	Zr	11.3	3.96 μg/g	90	Th	0.044	30.9 ng/g
41	Nb	0.76	265 ng/g	92	U	0.0093	8.4 ng/g
42	Mo	2.60	1.02 μg/g				

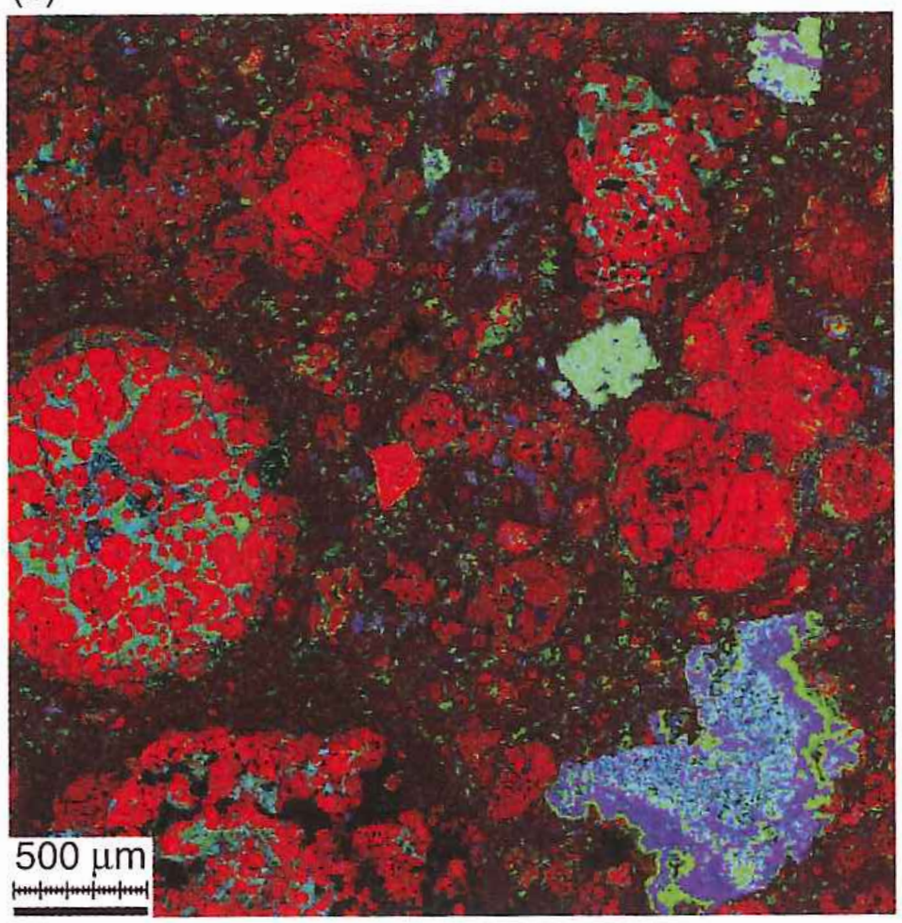
Asteroids







(b)



(d)

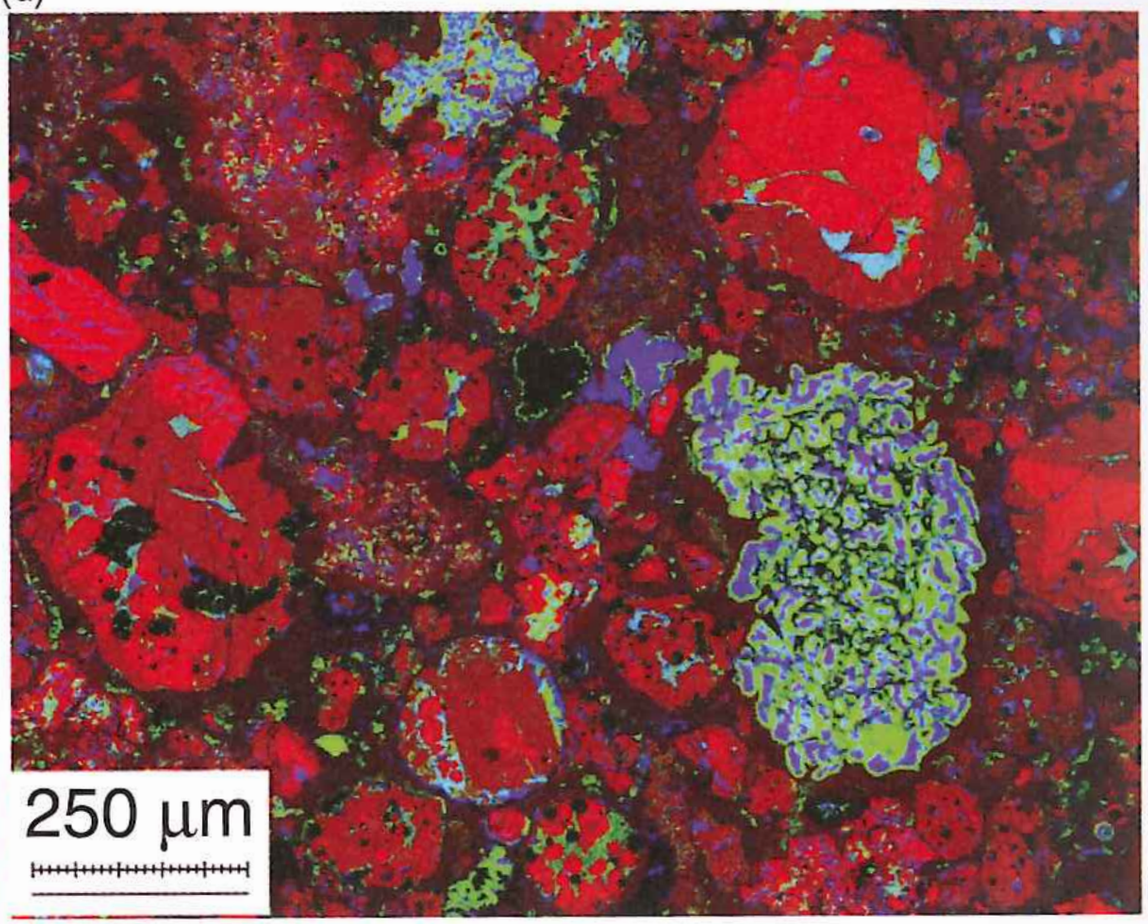


Figure 8.17

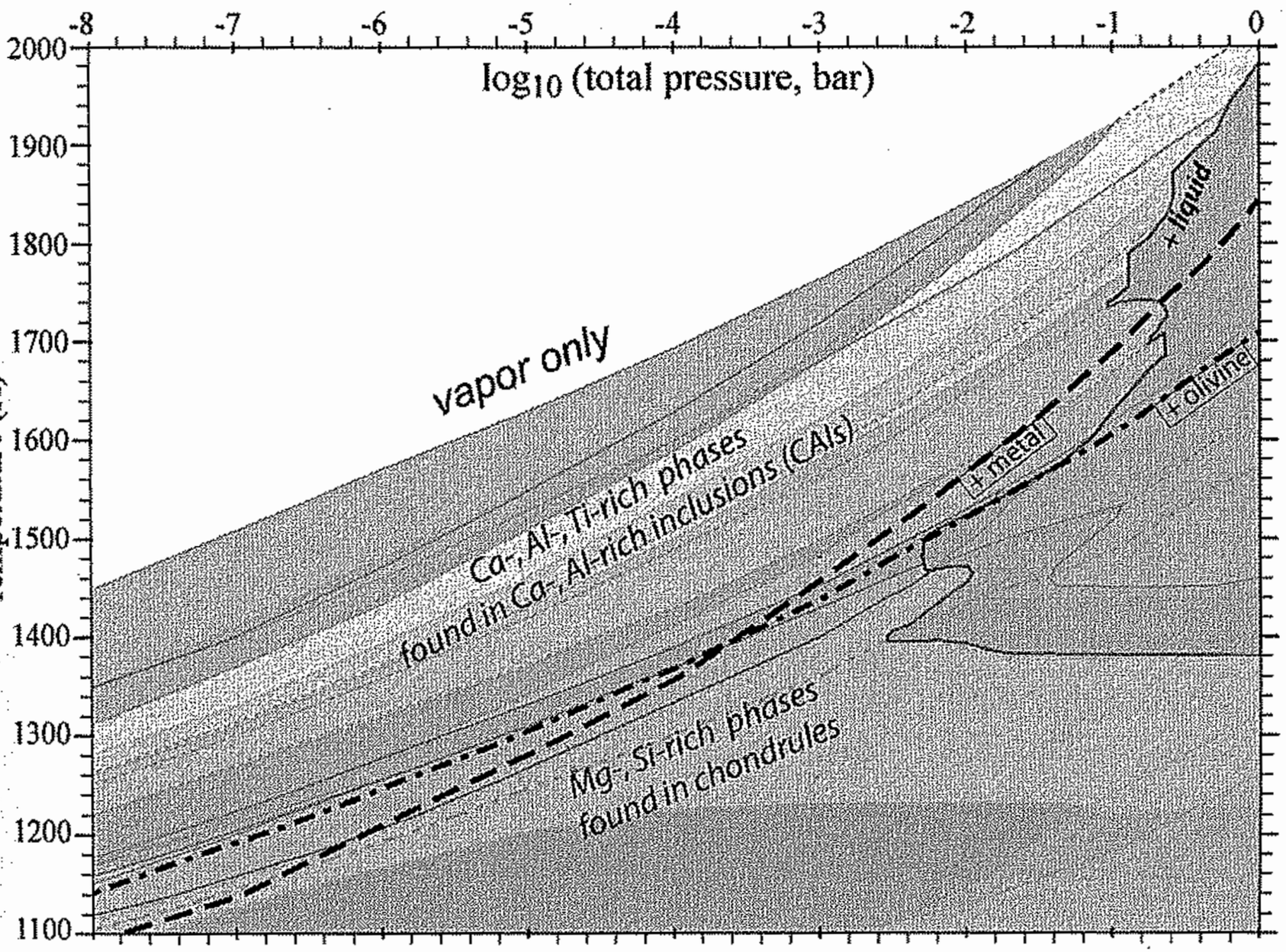


Figure 8.21 Phase diagram showing the principal constituents of chondrules and CAIs. The various lines show the condensation boundaries for different minerals, with the most important constituents labeled. (Ebel 2006)

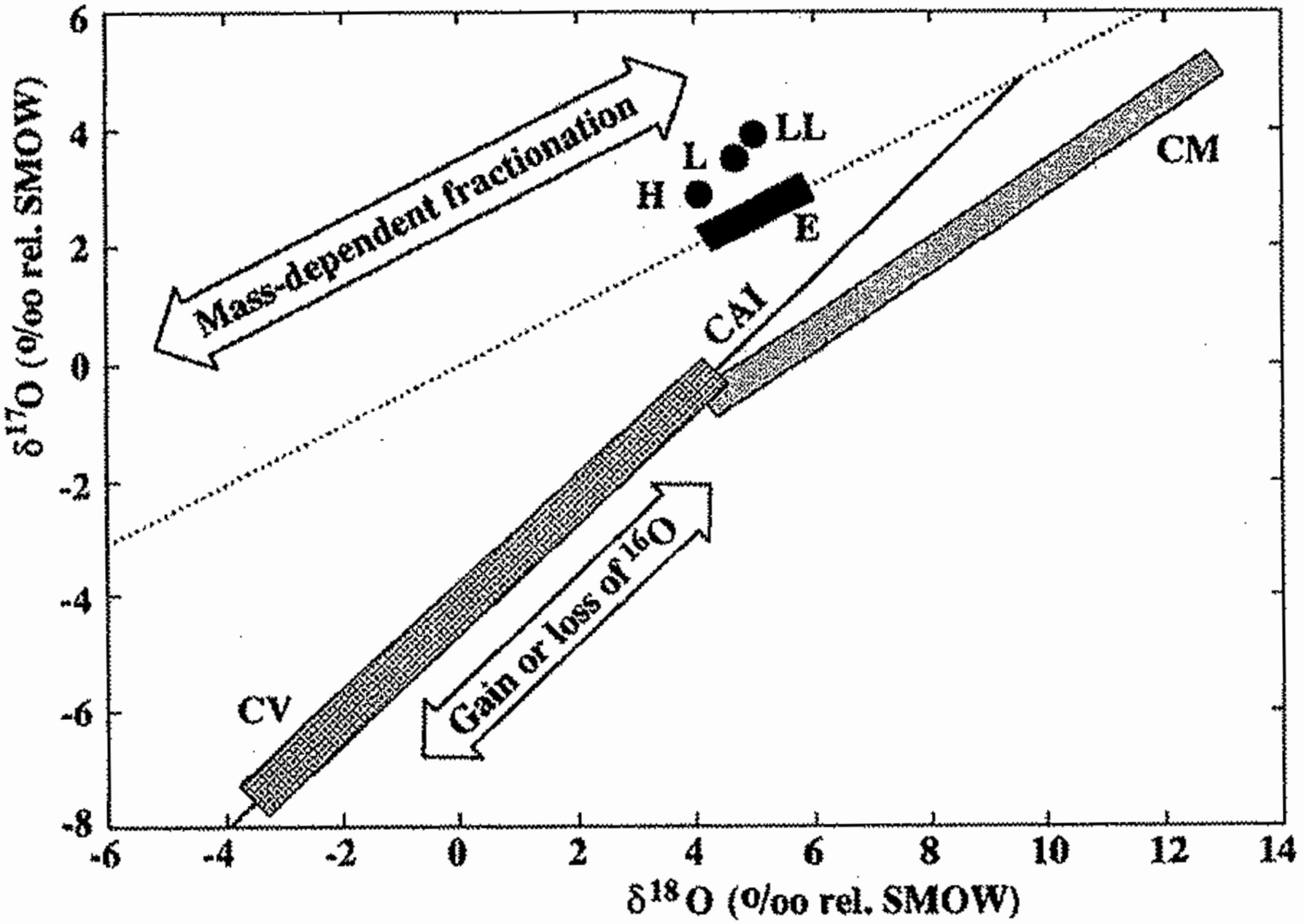
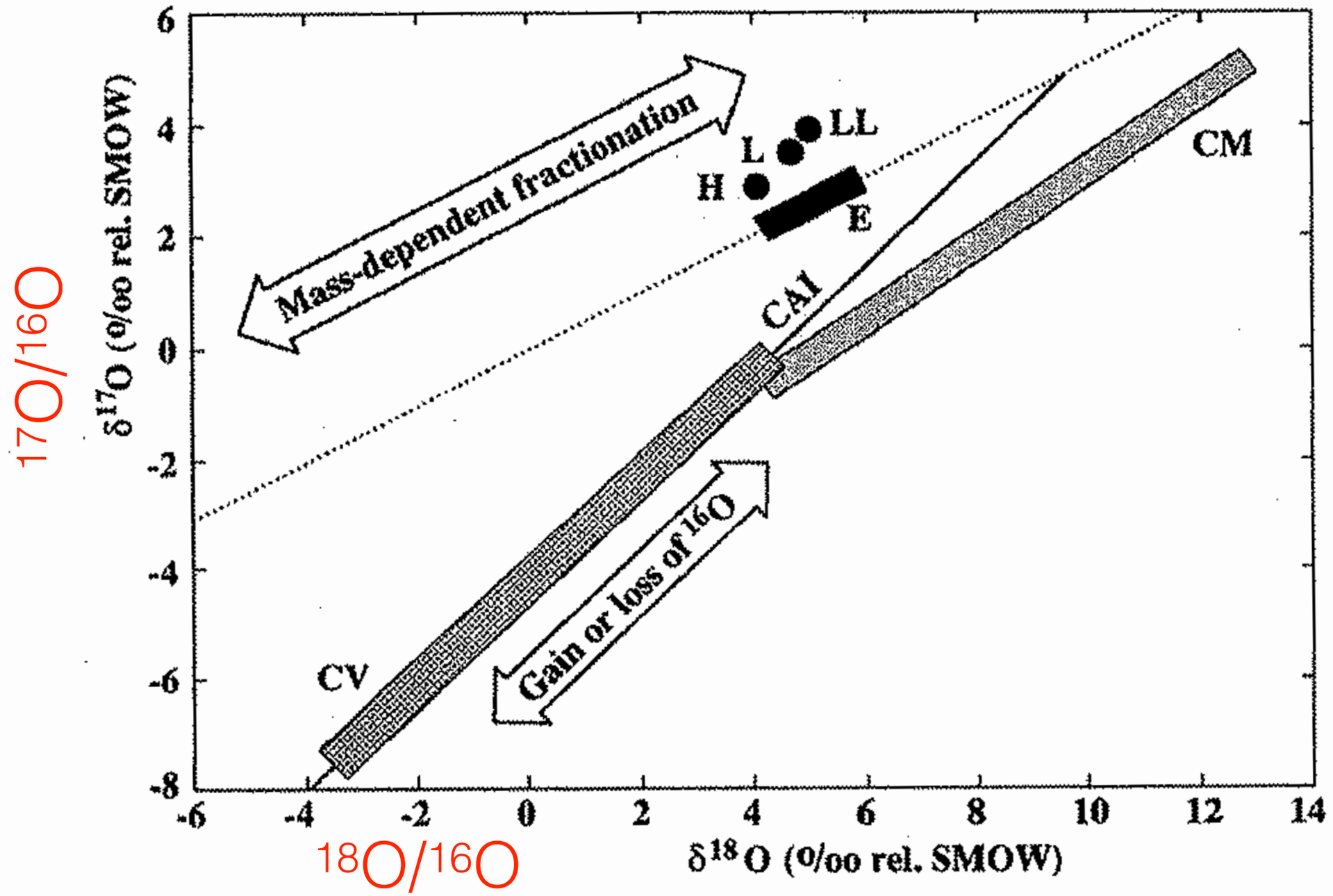


Figure 8.16 Plot showing the distribution of the three stable oxygen isotopes in various Solar System bodies. Isotope abundance ratios are shown relative to the Standard (terrestrial) Mean Ocean Water (SMOW), with units being parts per thousand variations. The dotted line represents the mass-dependent fractionation pattern observed in terrestrial samples. (Kerridge 1993)



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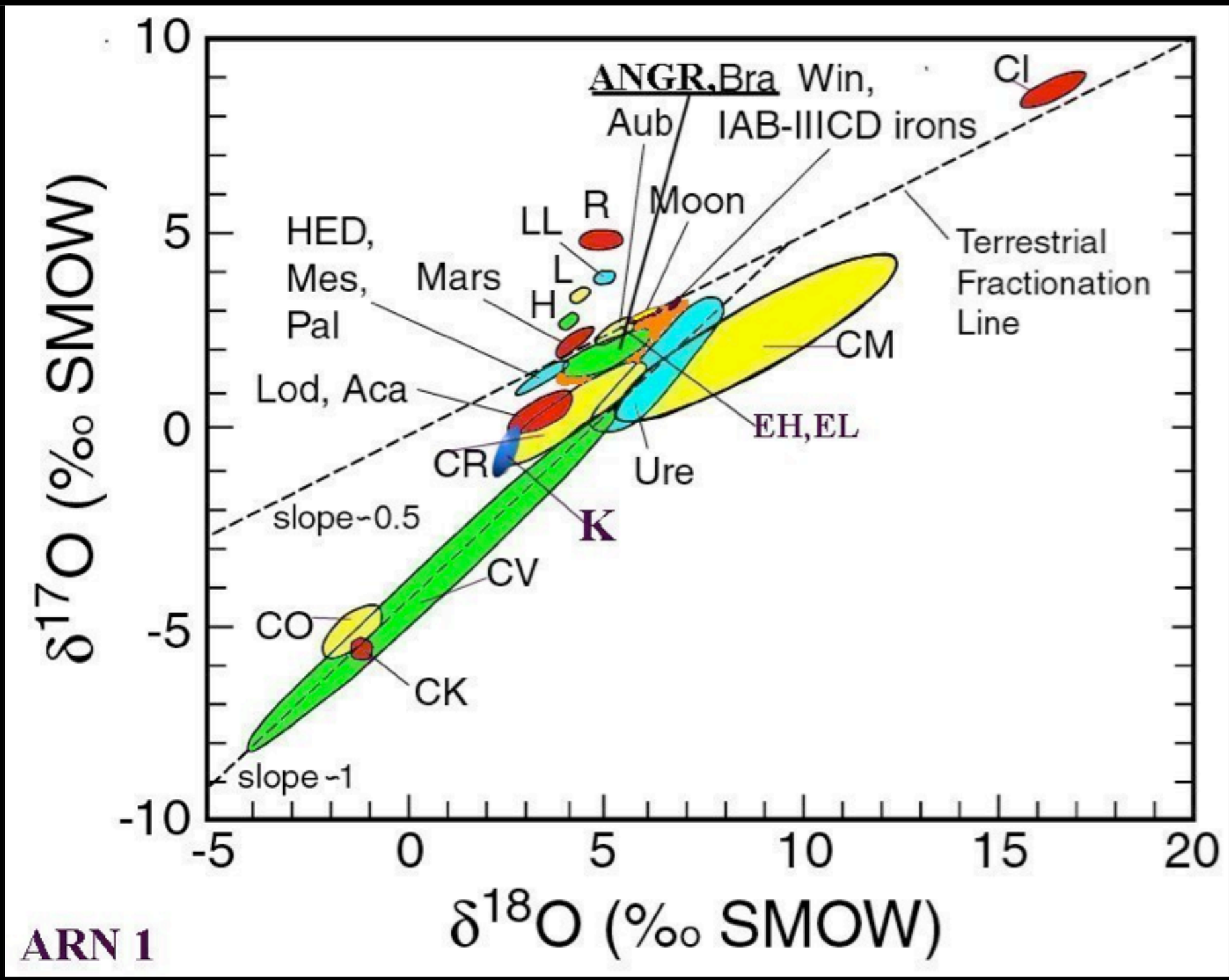
ANGR,Bra
Win,
Aub
IAB-IIICD irons
CI
R
Moon
LL
L
H
HED,
Mes,
Pal
Mars
Terrestrial
Fractionation
Line
CM
Lod, Aca
EH,EL
CR
Ure
K
slope~0.5
CV
CO
CK
slope~1
10
5
0
-5
-10
-5
0
5
10
15
20
δ17O (‰ SMOW)
δ18O (‰ SMOW)
ARN 1

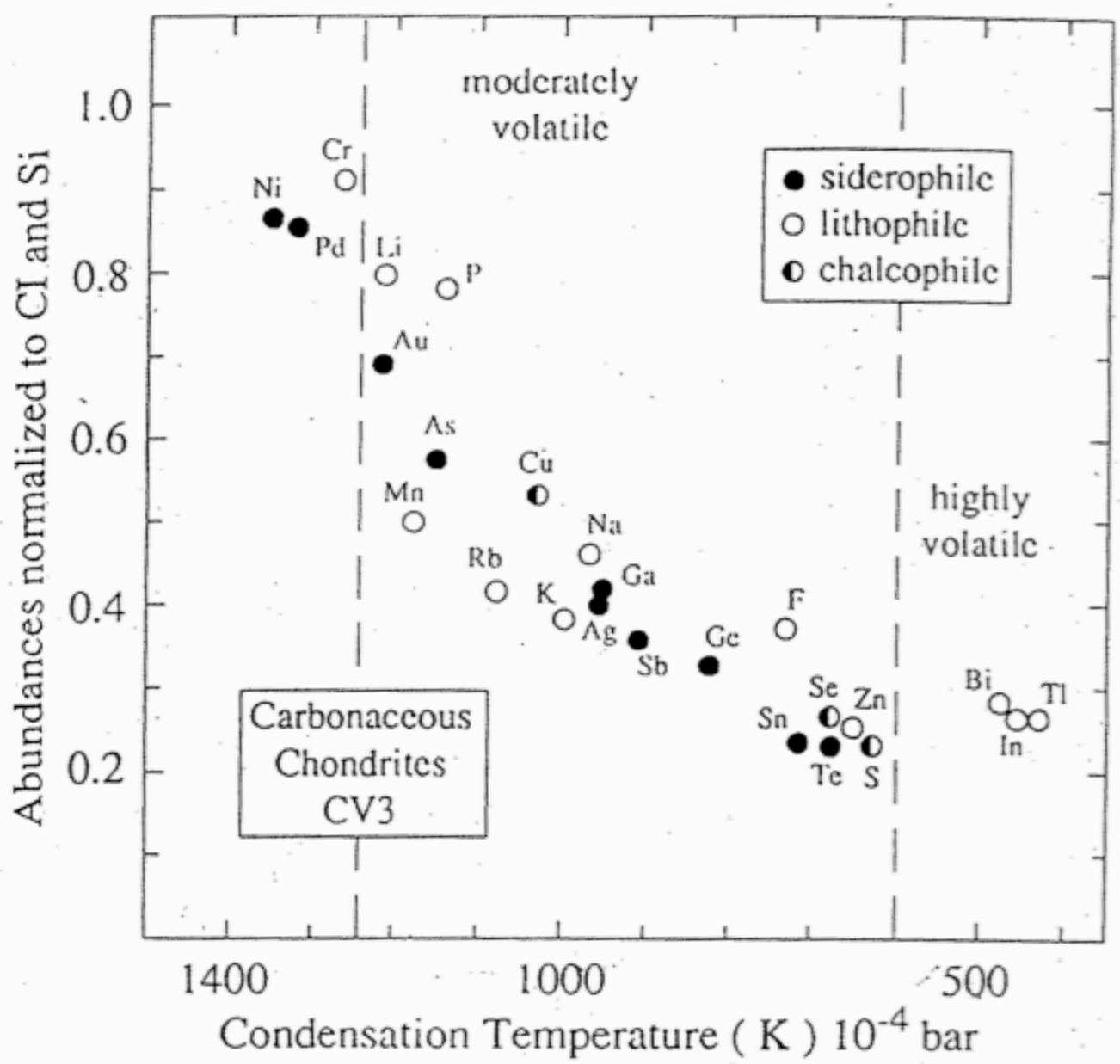

FIGURE 8.15 The abundances of moderately volatile elements in bulk CV chondrites compared to their abundances relative to silicon in CI chondrites are plotted against the condensation temperatures of the elements in a solar composition gas. Note the gradual decrease in abundance with decreasing condensation temperature, and the lack of dependence of abundances on the geochemical character of the elements.

Implies significant