Thermal and Dynamic History of Planets
Planetary Volcanism and Crustal Evolution

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Day 2 – The thermal evolution of Mars

Part I – The mantle source
A geochemical model of the Martian mantle

Part II – Petrological constraints on the thermal evolution of the mantle

Part III – Outstanding questions

Part III – The mantle source

There are different ways to determine the composition of the martian mantle

Cosmochemical models

a) Assume Mars has a chondritic composition and results from a mixture of different group of meteorites. Contrained by oxygen isotopes of different groups of chondrites and Martian meteorites (Sanloup et al. 1999)

b) Use element ratio in Martian meteorites to determine the composition of the primitive mantle (Dreibus and Wanke 1985).

Geophysical inversion

c) Inversion of Martian second degree tidal Love number, tidal dissipation factor, mean density and moment of inertia for mantle composition and thermal state using a stochastic sampling algorithm.

Gibbs energy minimization is used to compute the stable mineralogy of the Martian mantle in the model system CaO–FeO–MgO–Al2O3–SiO2.

The formation of Mars

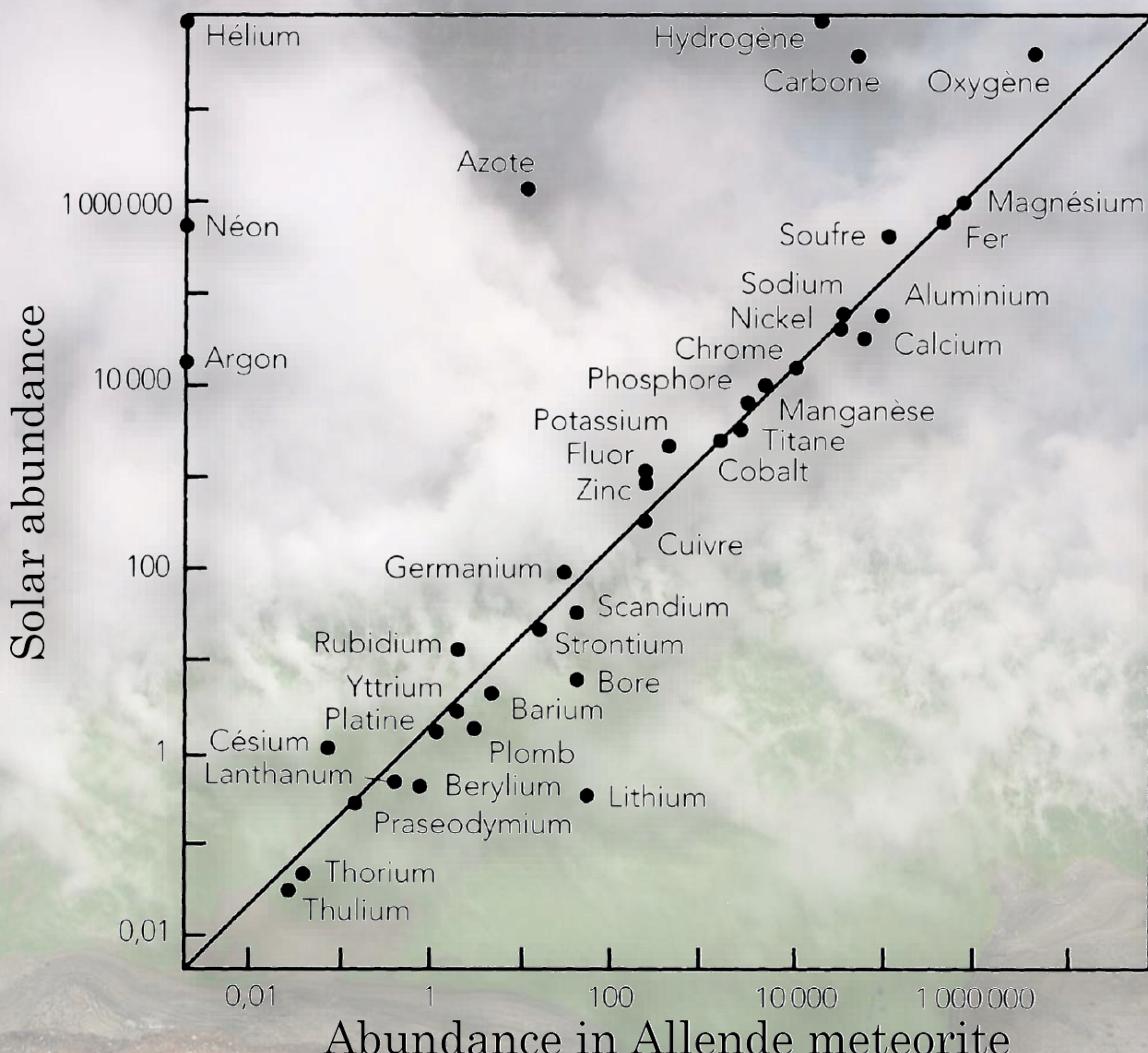
Mars, as the other terrestrial planets, formed from condensation of the solar nebula gas, followed by the accretion of planetesimals.

Composition of the solar nebula

Composition of Mars

W. Hartmann – 2005 – Clearing out the solar nebula. The first planetesimals.

Accretion – Composition of the gas of the Nebula



Accretion – Cosmochimical behavior

Cosmochemical Periodic Table of the Elements in the Solar System

abund. / EL / Tc (K)
...... Si = 1e6 atoms
...... element symbol
...... 50% condensation temperature at 1e-4 bar ...... refractory / common / volatile / highly volatile

s=solid solution

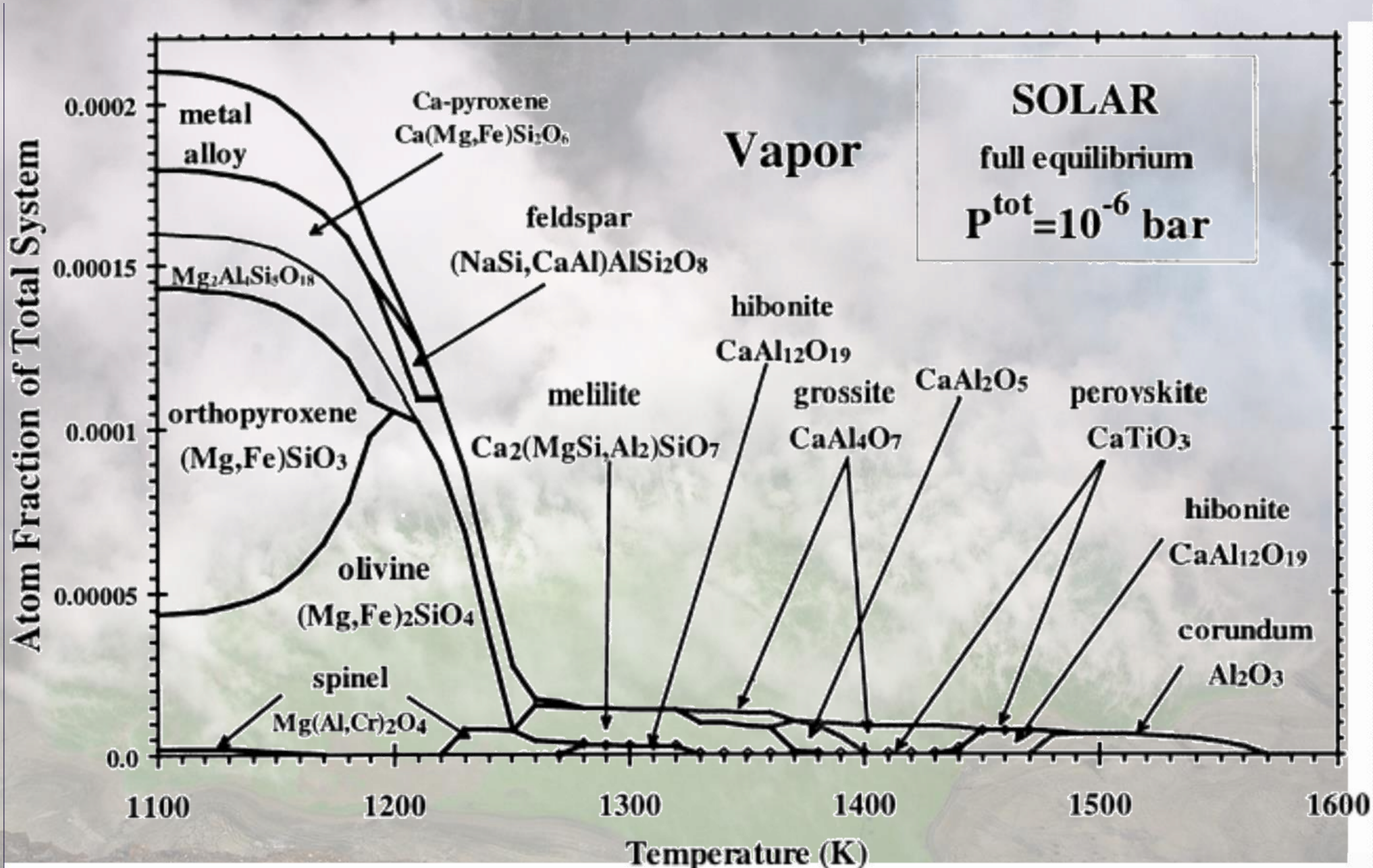
box color: lithophile, chalcophile, siderophile, atmophile

2.43e10 H																	2.343e9 He <3
55.47 Li 1142 s	0.7374 Be 1452 s											17.32 B 908 s	7.079e6 C 40	1.950e6 N 123	1.413e7 O 180	841.1 F 734 s	2.148e6 Ne 9.1
57510 Na 958 s	1.020e6 Mg 1336											84100 Al 1653	1.000e6 Si 1310	8373 P 1229	444900 S 664	5237 Cl 948 s	102500 Ar 47
3692 K 1006 s	62870 Ca 1517	34.20 Sc 1659 s	2422 Ti 1582	288.4 V 1429 s	12860 Cr 1296 s	9168 Mn 1158 s	838000 Fe 1334	2323 Co 1352 s	47800 Ni 1353 s	527 Cu 1037 s	1226 Zn 726 s	35.97 Ga 968 s	120.6 Ge 883 s	6.089 As 1065 s	65.79 Se 697 s	11.32 Br 546 s	55.15 Kr 52
6.572 Rb 800 s	23.64 Sr 1464 s	4.608 Y 1659 s	11.33 Zr 1741	0.7554 Nb 1559 s	2.601 Mo 1590 s	Tc	1.900 Ru 1551 s	0.3708 Rh 1392 s	1.435 Pd 1324 s	0.4913 Ag 996 s	1.584 Cd 652 s	0.1810 In 536 s	3.733 Sn 704 s	0.3292 Sb 979 s	4.815 Te 709 s	0.9975 I 535 s	5.391 Xe 68
0.3671 Cs 799 s	4.351 Ba 1455 s	0.4405 La 1578 s	0.1699 Hf 1684 s	0.02099 Ta 1573 s	0.1277 W 1789 s	0.05254 Re 1821 s	0.6738 Os 1812 s	0.6448 Ir 1603 s	1.357 Pt 1408 s	0.1955 Au 1060 s	0.4128 Hg 252 s	0.1845 Tl 532 s	3.258 Pb 727 s	0.1388 Bi 746 s	Po	At	Rn
Fr	Ra	Ac	Rf	Ha	106	107	108	109	110	111	112						

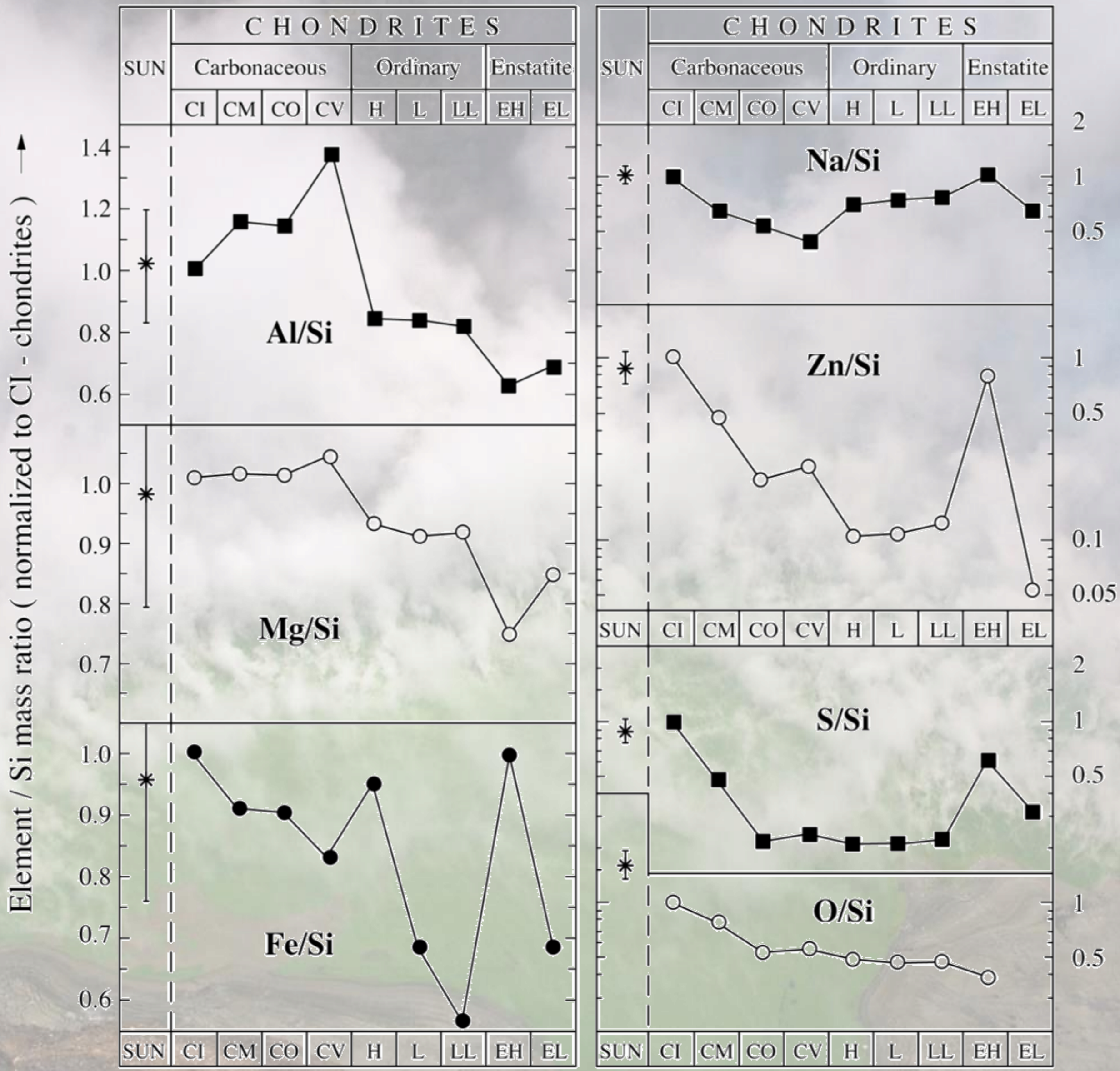
1.169 Ce 1478 s	0.1737 Pr 1582 s	0.8355 Nd 1602 s	Pm	0.2542 Sm 1590 s	0.09513 Eu 1356 s	0.3321 Gd 1659 s	0.05907 Tb 1659 s	0.3862 Dy 1659 s	0.08986 Ho 1659 s	0.2554 Er 1659 s	0.0370 Tm 1659 s	0.2484 Yb 1487 s	0.03572 Lu 1659 s
0.03512 Th 1659 s	Pa	9.31e-3 U 1610 s	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

K. Lodders, 2003, Solar System Abundances and Condensation Temperatures of the Elements, *Astrophys. J.* 591, 1220-1247

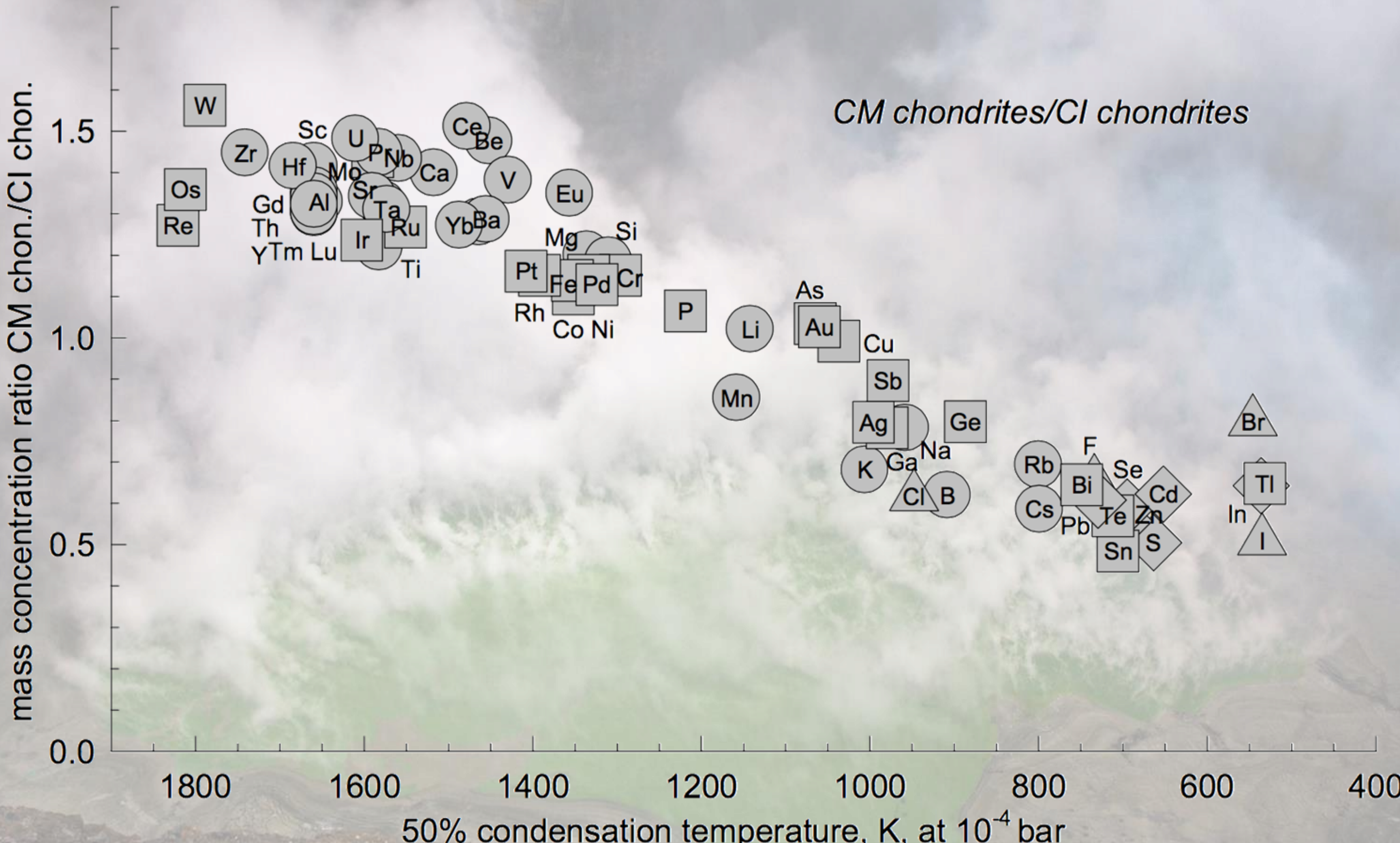
The formation of Mars

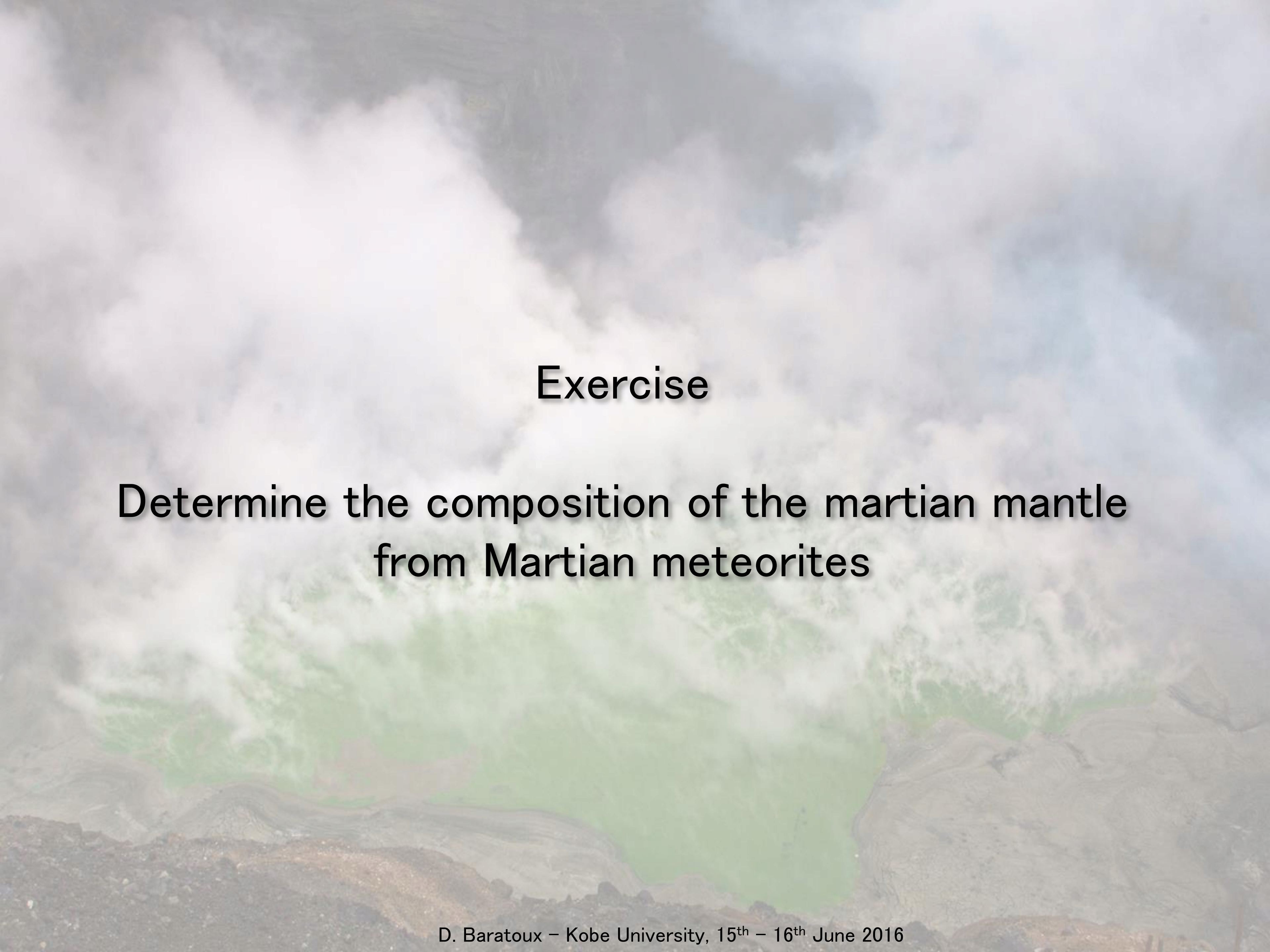


The formation of Mars



The formation of Mars



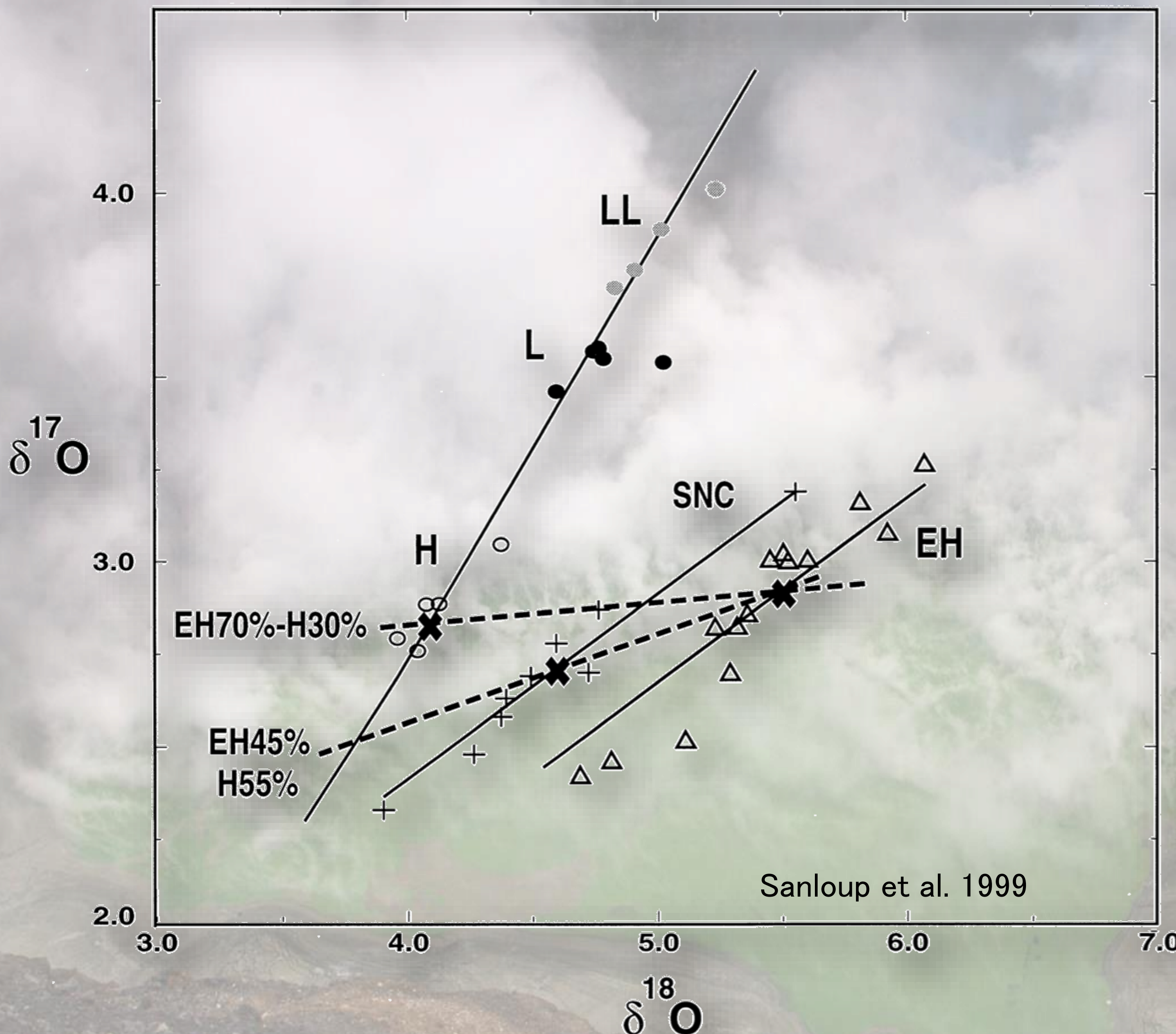


Exercise

Determine the composition of the martian mantle from Martian meteorites

D. Baratoux – Kobe University, 15th – 16th June 2016

Comparison with Sanloup et al. 1999



Comparison with Sanloup et al. 1999

Model	EH45:H55	EH70:H30	Anderson, 1972	Wänke and Dreibus, 1988
Mantle	0.76	0.72	0.88	0.78
MgO	27.3	27.3	27.4	30.2
SiO_2	47.5	51.0	40.0	44.4
Al_2O_3	2.5	2.5	3.1	3.0
TiO_2	0.1	0.1	0.1	0.1
CaO	2.0	2.0	2.5	2.4
MnO	0.4	0.4	0.2	0.5
Na_2O	1.2	1.3	0.8	0.5
Cr_2O_3	0.7	0.6	0.6	0.8
FeO	17.7	11.4	24.3	17.9
Mg/Si (mole)	1.17	0.98	1.53	1.36
Mg#	0.72	0.80	0.67	0.75
Core	0.23	0.28	0.12	0.22
Fe	76.6	76.3	72.0	77.8
S	16.2	17.4	18.6	14.2
Ni	7.2	6.3	9.3	8.0

Comparison with Khan et al. 2004

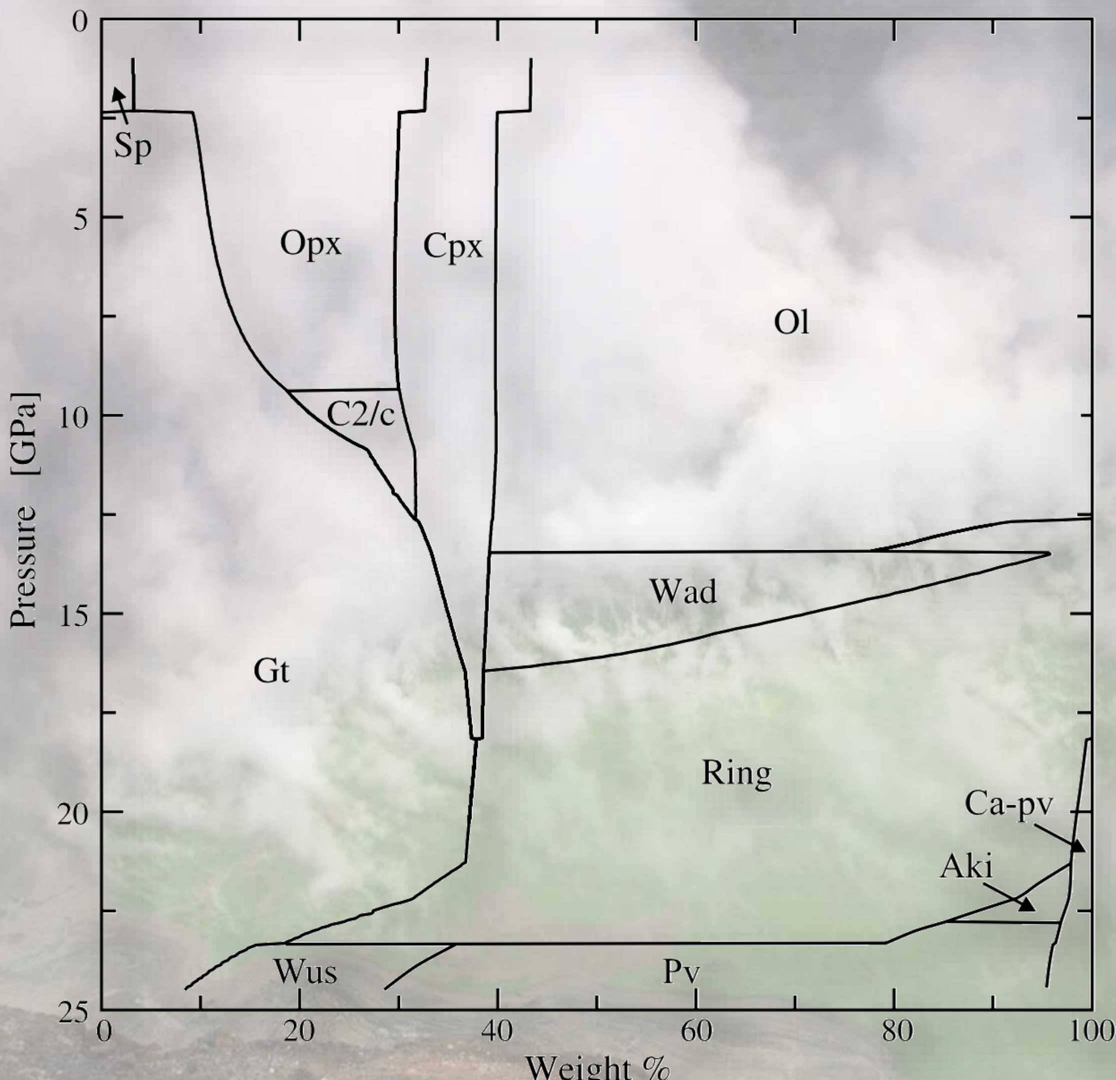
We invert the most recent determinations of Martian second degree tidal Love number*, tidal dissipation factor, mean density and moment of inertia for mantle composition and thermal state using a stochastic sampling algorithm. We employ Gibbs energy minimization to compute the stable mineralogy of the Martian mantle in the model system CaO–FeO–MgO–Al_2O_3–SiO.

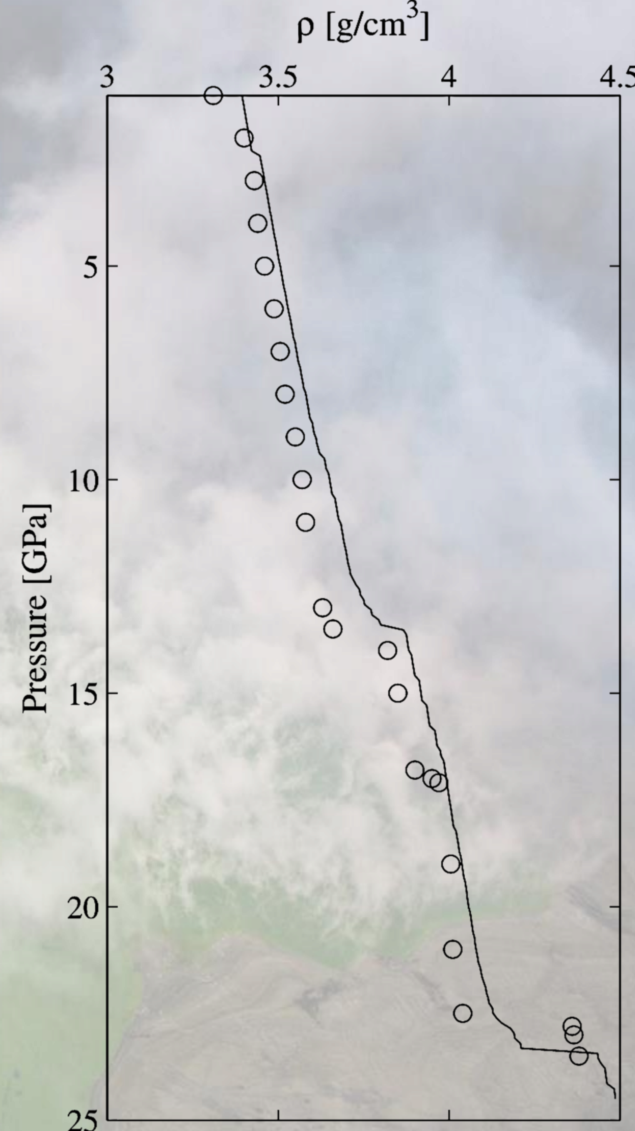
Table 4. Summary of Derived Bulk Compositions (Most Probable Values), Various Literature Estimates and Some Average Meteorite Compositions From *Jarosewich* [1990][a]

Study	CaO	FeO	MgO	Al_2O_3	SiO_2	Mg#
This study	2.2	17	33	2.5	44	0.77
Morgan and Anders	5.2	15.8	29.8	6.4	41.6	0.77
Wänke and Dreibus (SNC)	2.4	17.9	30.2	3	44.4	0.75
Sanloup et al. (EH45:H55)	2	17.7	27.3	2.5	47.5	0.72
Sanloup et al. (EH70:H30)	2	11.4	27.3	2.5	51	0.8
Lodders and Fegley	2.35	17.2	29.7	2.9	45.4	0.75
CM2	1.9	22.1	19.9	2.2	28.9	0.62
CV3	2.6	26.8	24.6	3.2	34.0	0.62
H	1.7	10.3	23.3	2.1	36.6	0.8
L	1.9	14.5	24.7	2.3	39.7	0.75
LL	1.9	17.4	25.2	2.2	40.6	0.72

*The Love number are dimensionless parameters that measure the rigidity of a planetary body and the susceptibility of its shape to change in response to a tidal potential.

Comparison with Khan et al. 2004





Exercise – Review and discuss the advantages and difficulties with each approach

Dreibus and Wanke 1985

Sanloup et al. 1999

Khan et al. 2004

Exercise – Review and discuss the difficulties with each approach

Dreibus and Wanke 1985

– Are martian meteorites representative ?
– Assumption for Ca, Al, Si, Mg – what is Si/Mg non-chondritic ?

Sanloup et al. 1999

– Assumption that Mars can be reproduces from the present collection of chondrites.
– P and K were not estimated, and are important during melting

Khan et al. 2004

– Applied "only" to the CaO-FeO-MgO-Al2O3-SiO2 system.
– One significant advantage: provide also constraints on mineralogy and density profile.