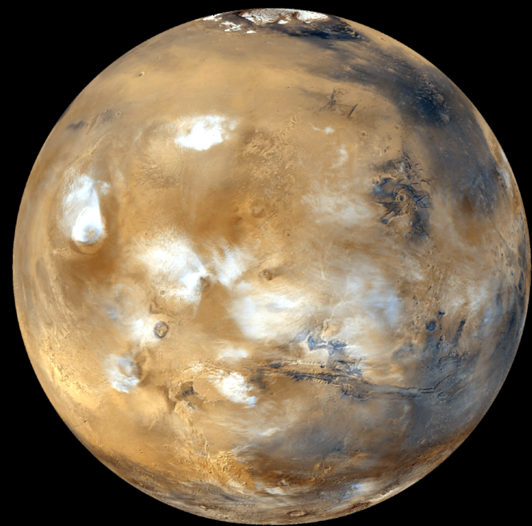
Formation of terrestrial planet atmospheres



Lindy Elkins-Tanton

MIT

NASA/JPL

Outline

Opportunities for a planet to obtain an atmosphere:

1. Capture of nebular gases
2. Outgassing of planetary materials
3. Cometary and other impacts

Ways to calculate outgassing

1. Meteorite compositions
2. Models

Chemistry and physics of degassing

1. Reducing vs oxidizing atmosphere
2. Collapse to an ocean

Results for Earth, Mars, exoplanets

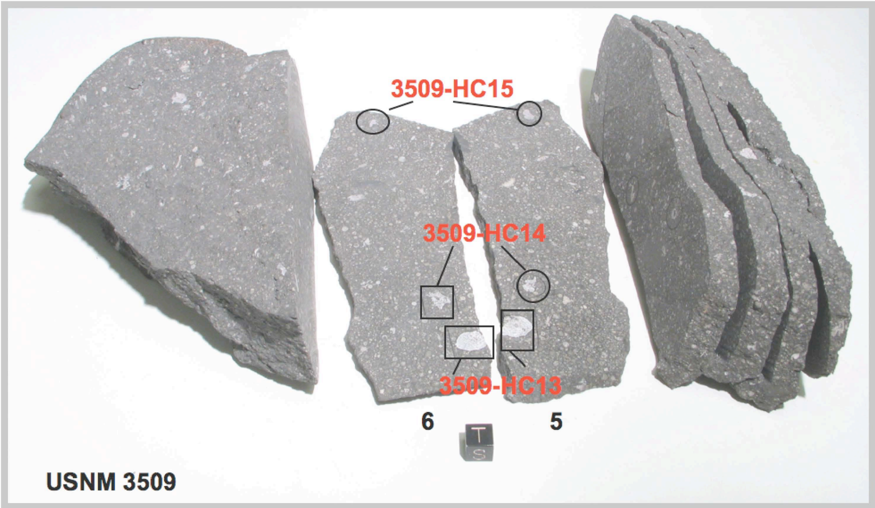
TABLE 5

PHOTOSPHERIC Z/X IN ELEMENTAL ABUNDANCE COMPILATIONS

Z/X	Year	Reference
0.0270	1984	1
0.0267	1989	2
0.0245	1993	3
0.0244	1996	4
0.0229	1998	5
0.0208	2002	6
0.0177	2003	7

REFERENCES—(1) Grevesse 1984; (2) Anders & Grevesse 1989; (3) Grevesse & Noels 1993; (4) Grevesse et al. 1996; (5) Grevesse & Sauval 1998; (6) Grevesse & Sauval 2002; (7) this work.

Lodders (2003)



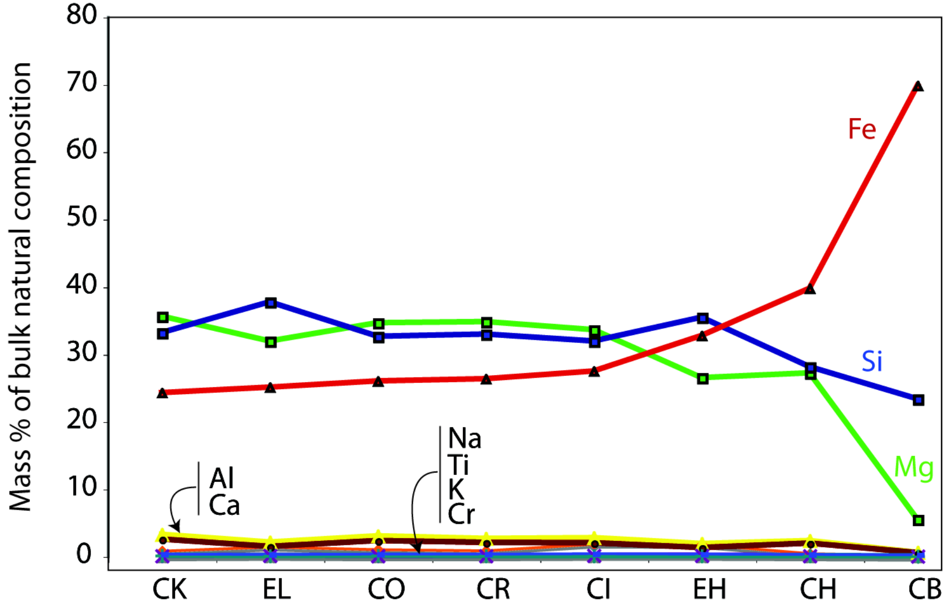
Allende carbonaceous chondrite (Sunshine et al., 2008)

Ibitira achondrite
(meteorites.com)

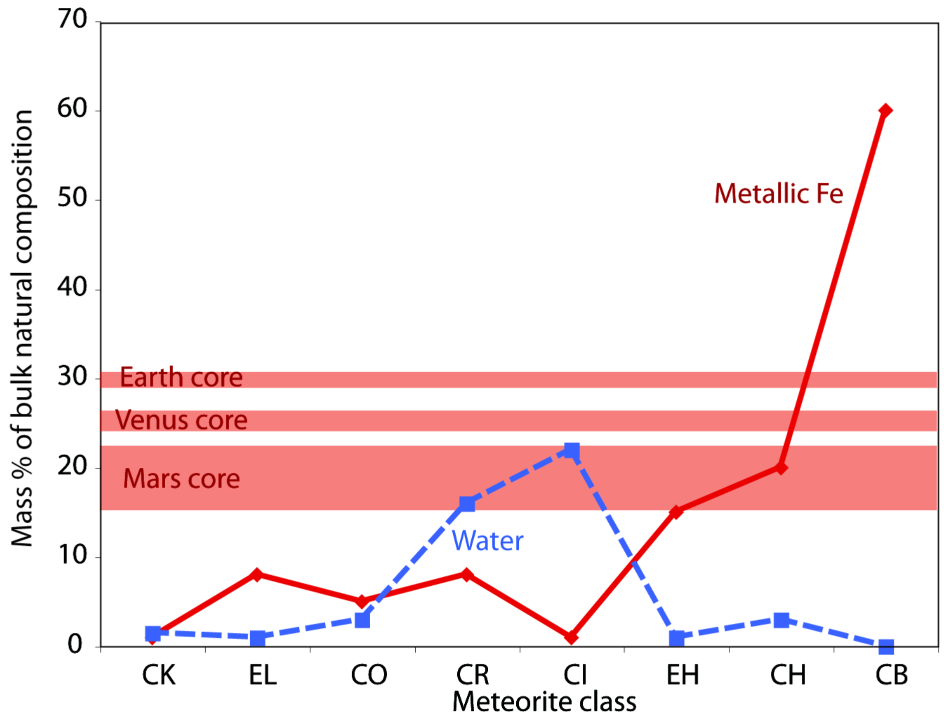
Axtell chondrite (American Museum of Natural History)

Brenham pallasite (American Museum of Natural History)

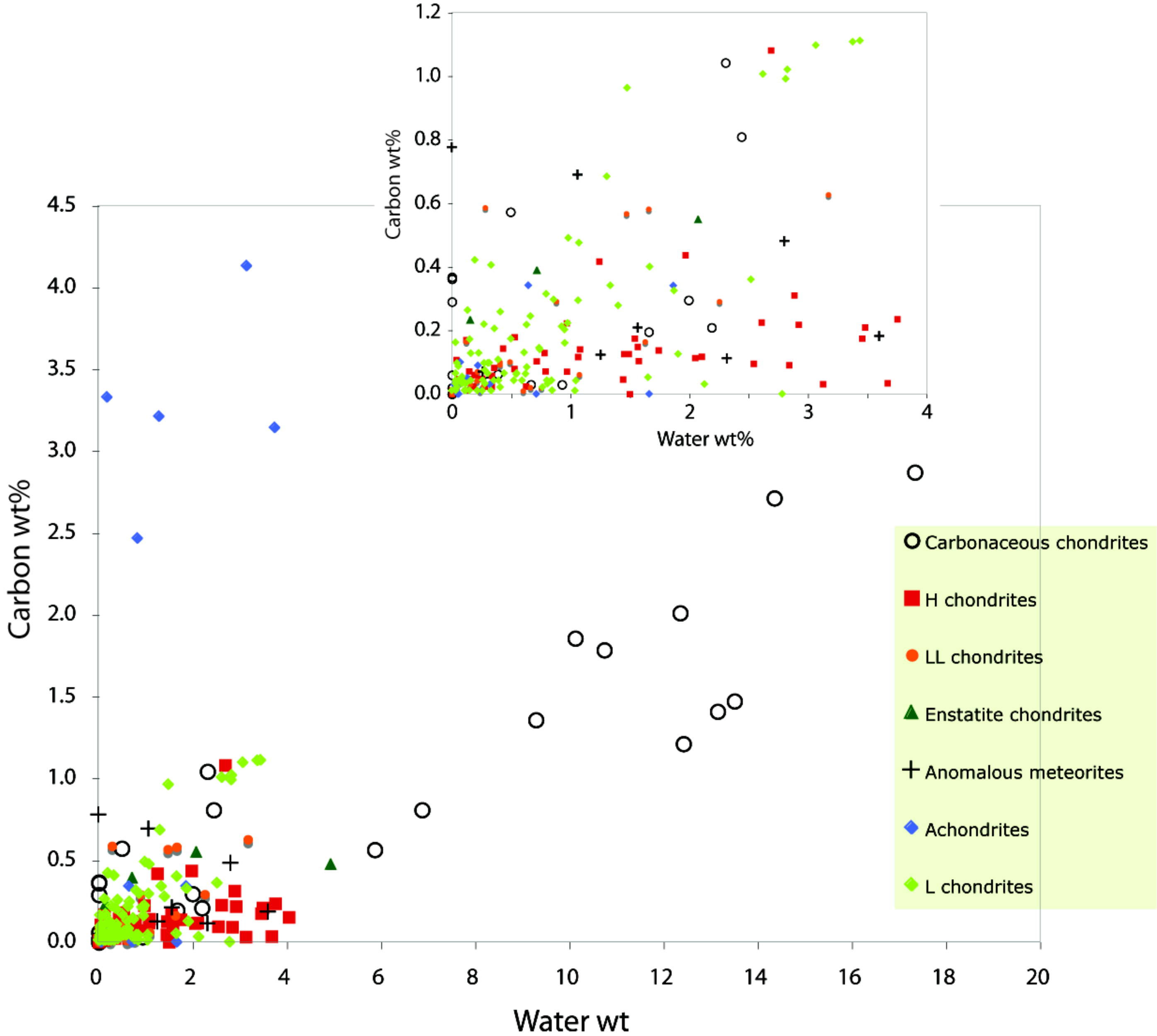
Meteorite compositions



Elkins-Tanton and Seager (2008)

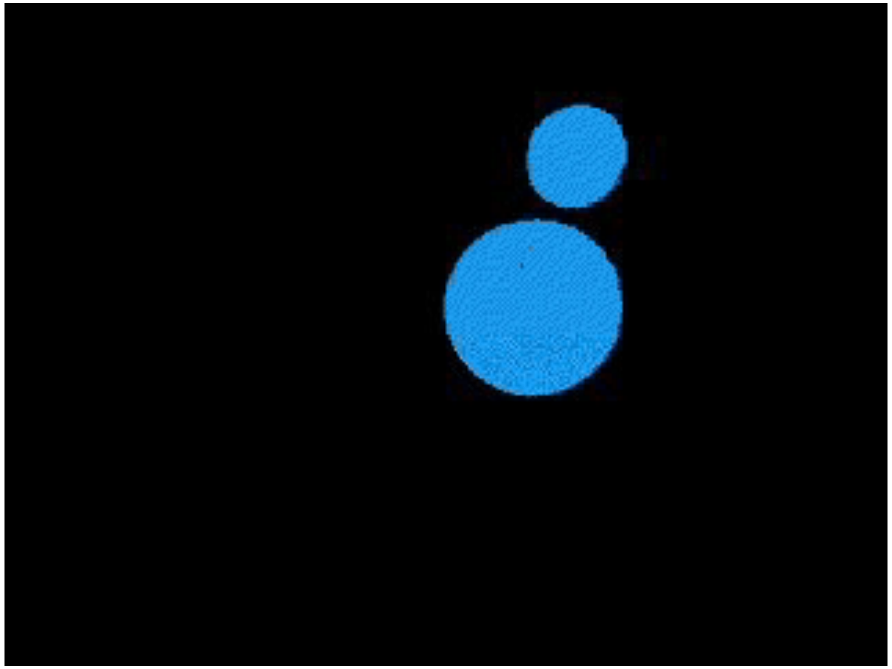


Water and carbon in meteorites



Data from Jarosewich (1990)

Planets are built, in their final stages, from giant impacts of planetesimals



Robin Canup, SWRI http://www.boulder.swri.edu/~robin/moonimpact/

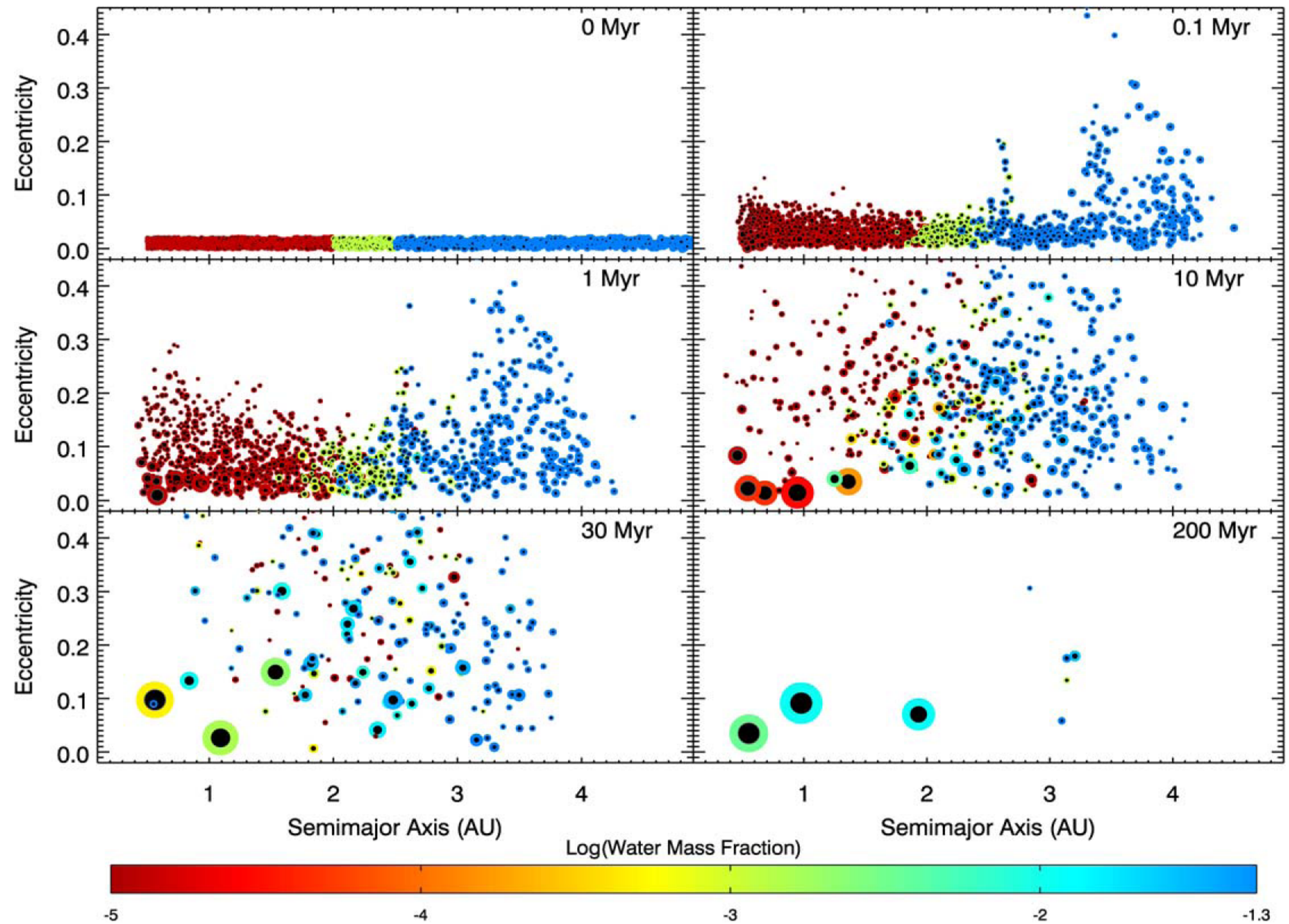


Fig. 2. Six snapshots in time from simulation 0, with 1885 initial particles. The size of each body corresponds to its relative physical size (i.e., its mass $M^{1/3}$), but is not to scale on the x axis. The color of each particle represents its water content, and the dark inner circle represents the relative size of its iron core. There is a Jupiter-mass planet at 5.5 AU on a circular orbit (not shown).

Raymond et al., 2006; see also Wiedenschilling, Safronov, Burbine

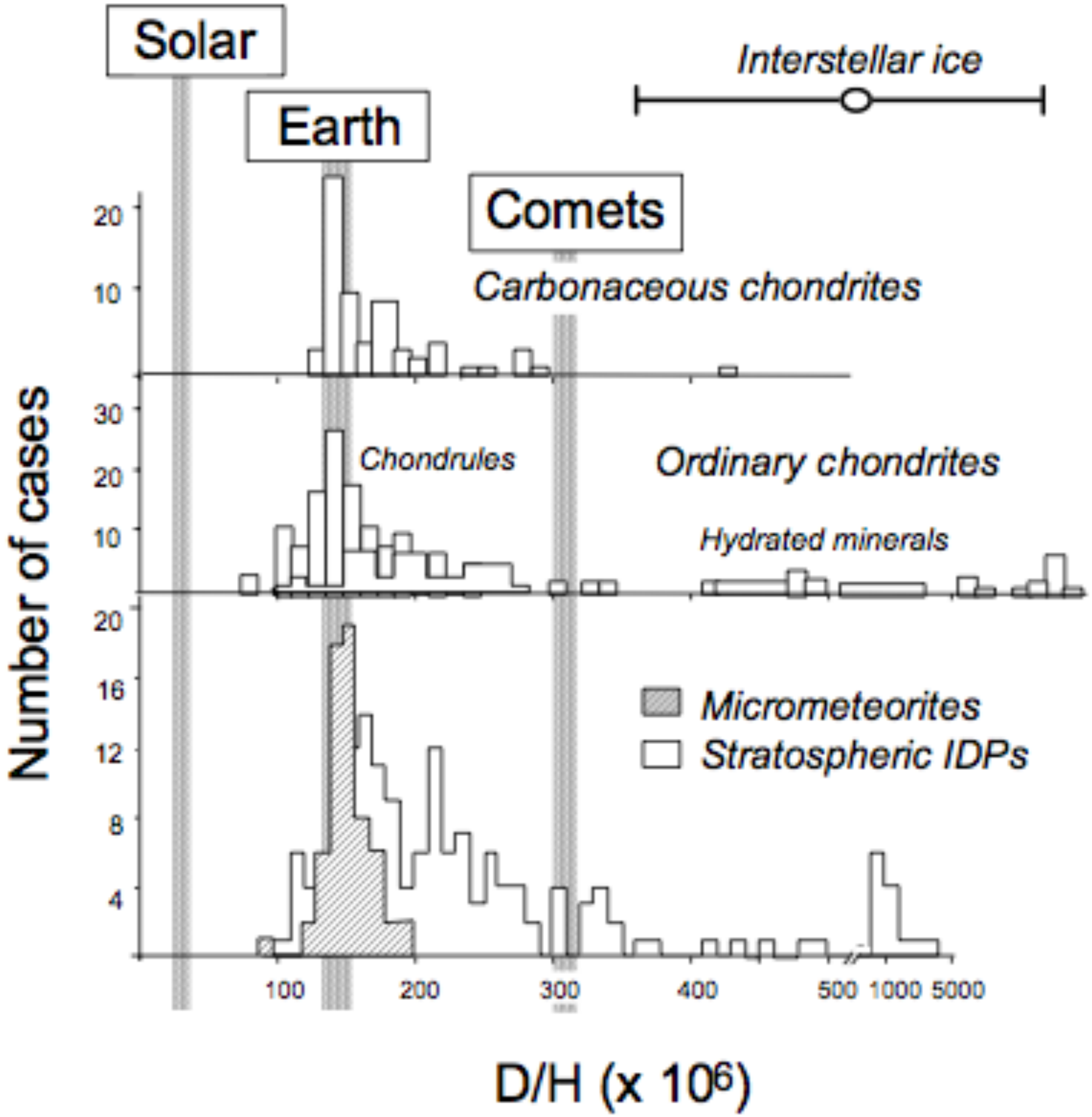


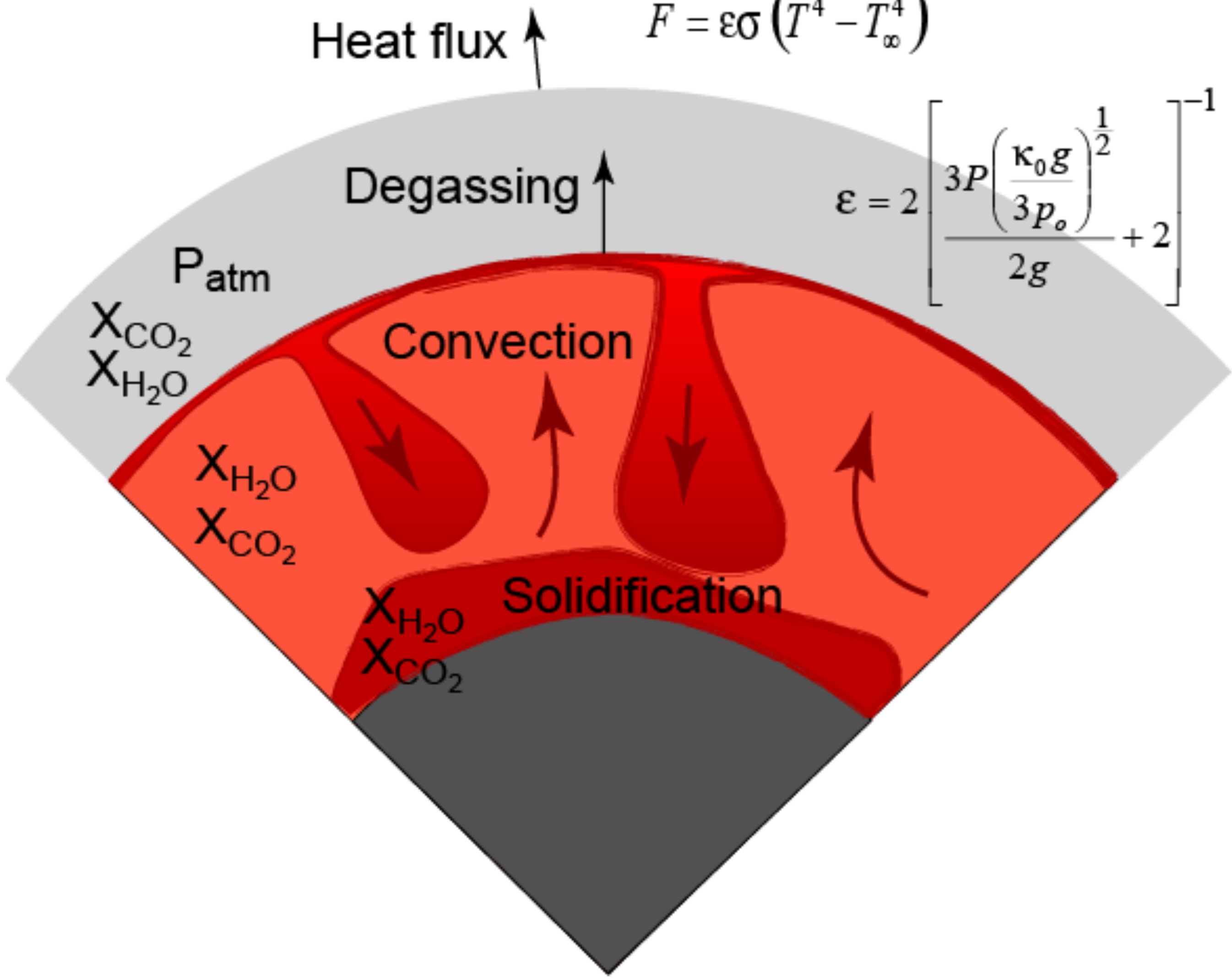
Figure 1. Histogram of D/H values among different solar system reservoirs, following Engrand et al. (1999a), Robert (2003), and references therein. The y-axis represents the number of analyses.

Marty and Yokochi (2006)

$$4\pi R^2 F = V\left[\rho H 4\pi r^2 + \rho C_p \frac{dT}{dr}\frac{4}{3}\pi\left(R^3 - r^3\right)\right]$$

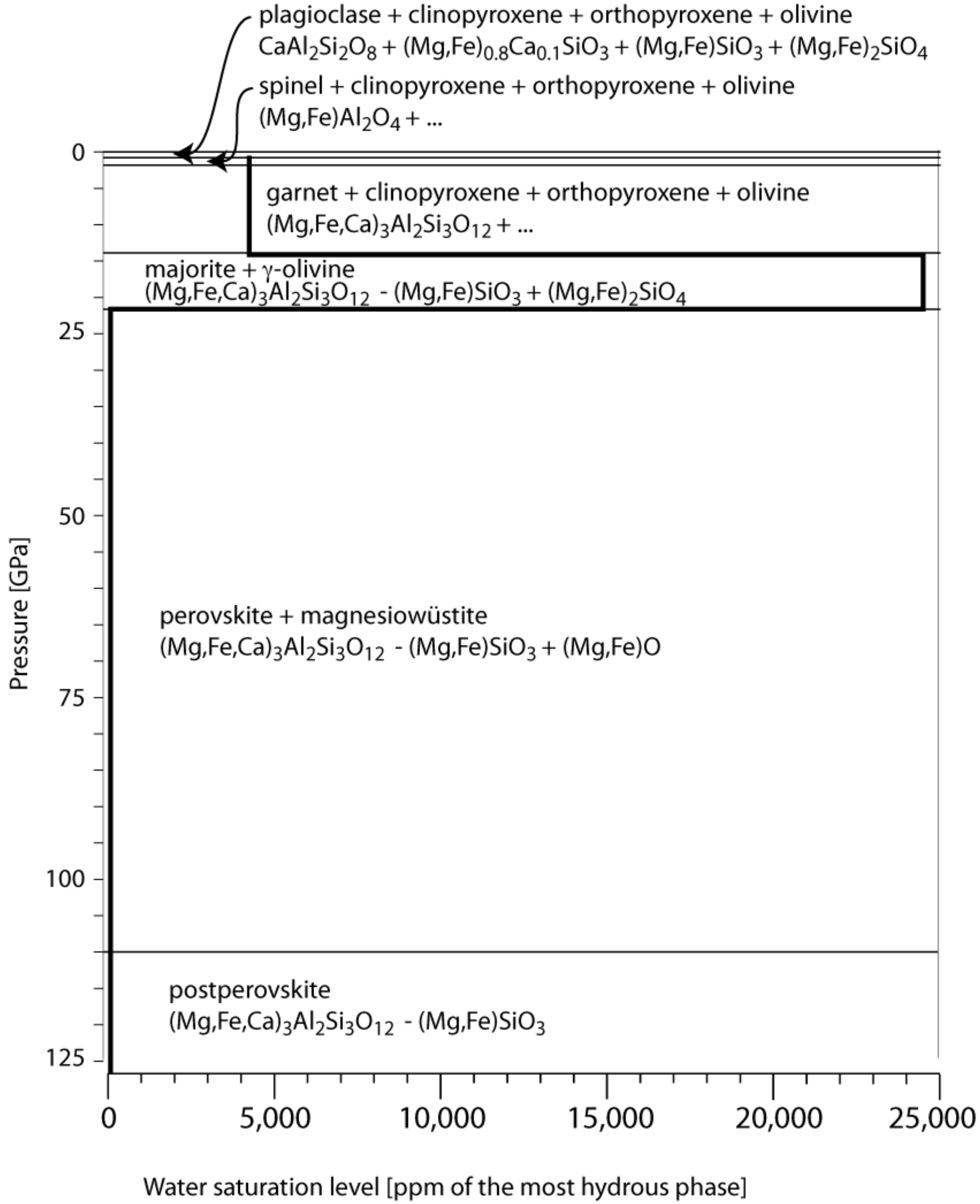
$$F = \varepsilon\sigma\left(T^4 - T_\infty^4\right)$$

$$\varepsilon = 2\left[\frac{3P\left(\frac{\kappa_0 g}{3p_o}\right)^{\frac{1}{2}}}{2g} + 2\right]^{-1}$$

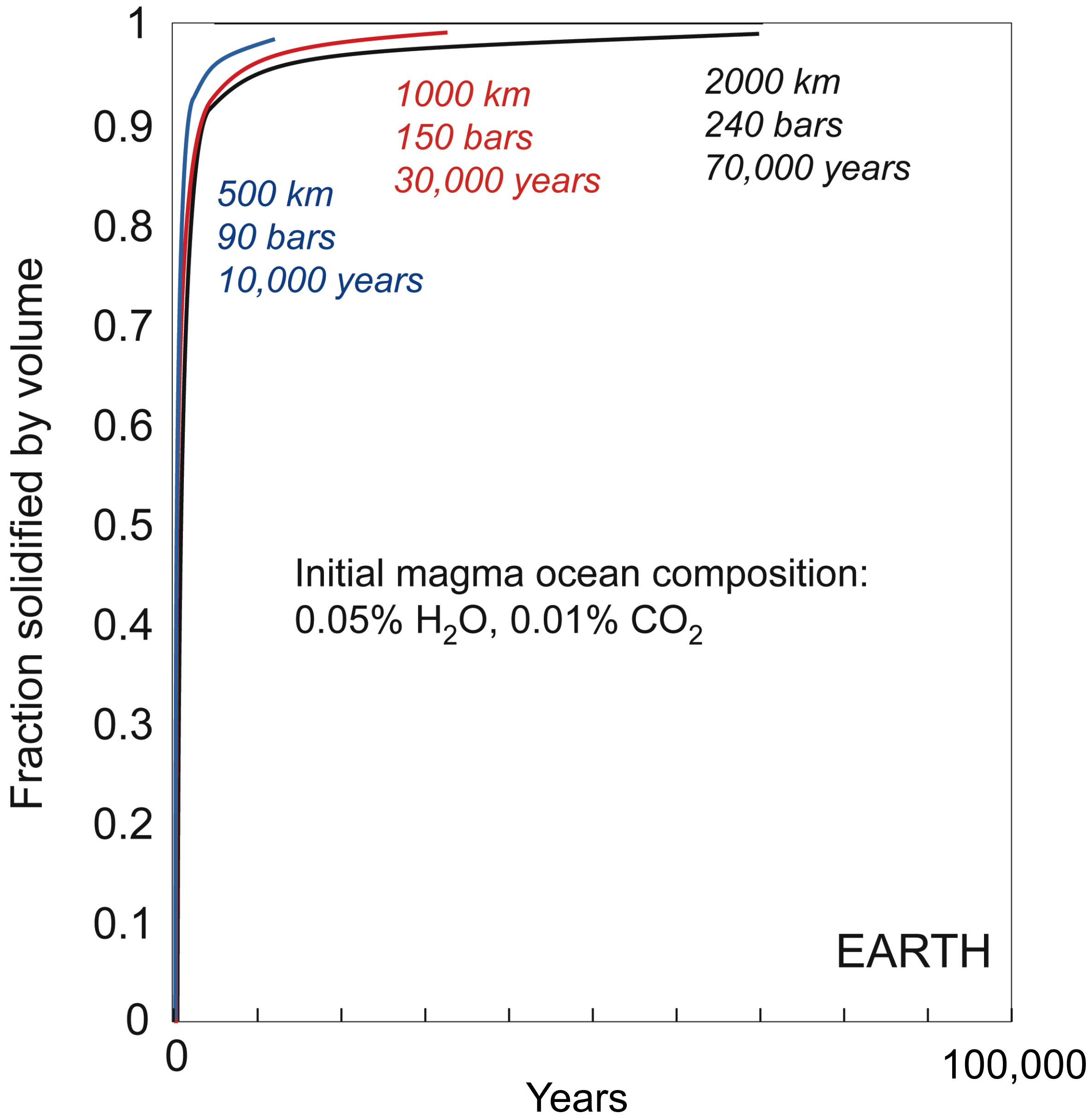


Abe, Zahnle, Solomatov, Kasting

Mantle minerals and water



Atmospheric growth



Atmospheric compositions

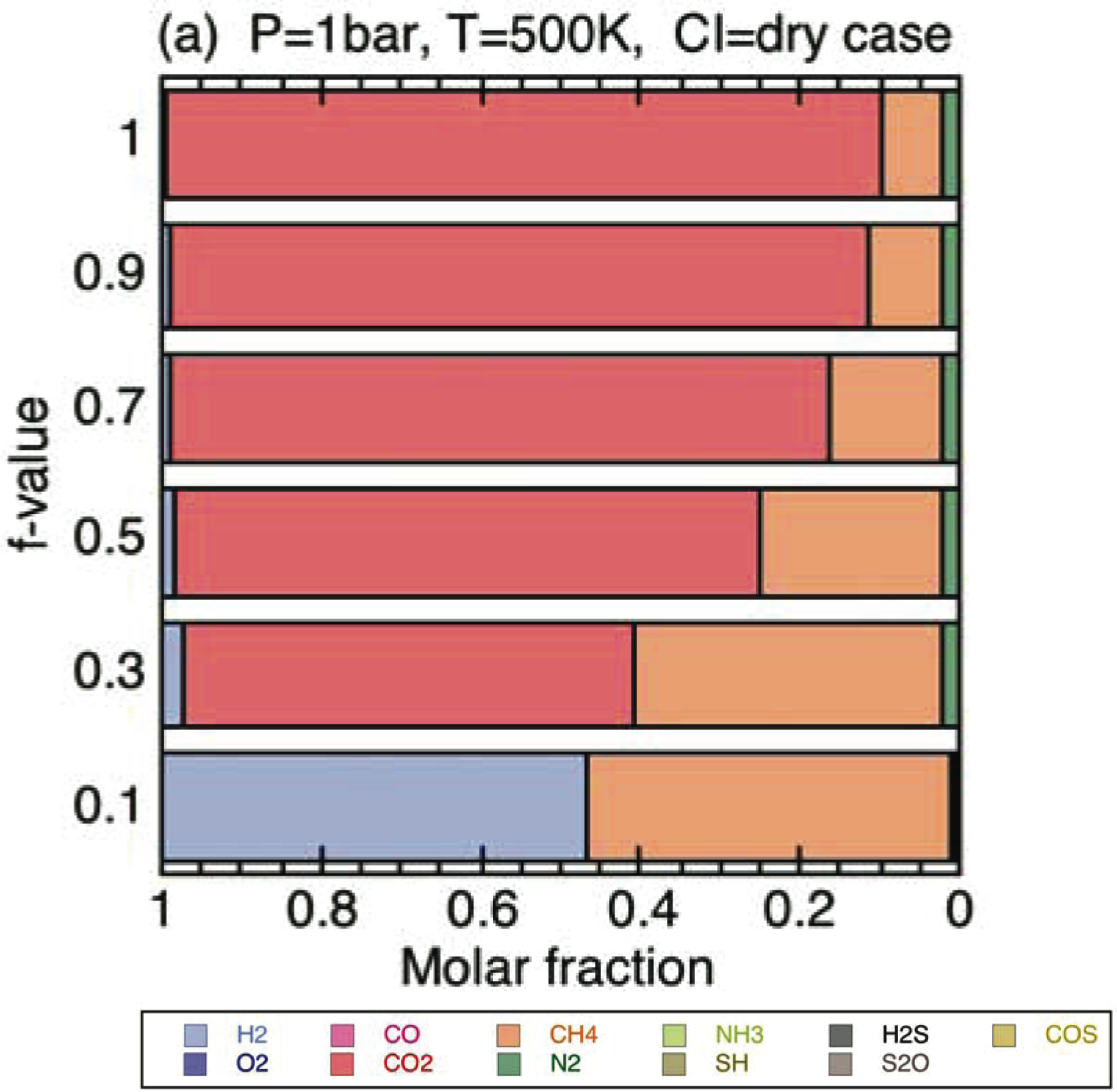


Figure 4. Dry gas composition for various values of parameter f. Water content in CI chondrite is about 6 wt% (dry case). Total pressure and temperature of each system are (a) P = 1 bar, T = 300 K, (b) P = 1 bar, T = 800 K, (c) P = 1 bar, T = 1300 K, and (d) P = 1 bar, T = 1500 K. This figure does not include water vapor since atmospheric water varies greatly due to condensation.

Hashimoto et al. (2007)

Table 1
Major gas compositions of impact generated atmospheres from chondritic planetesimals at 1500 K and 100 bars.

Gas (vol.%)	*CI*	*CM*	*CV*	*H*	*L*	*LL*	*EH*	*EL*
H_2	4.36	2.72	0.24	**48.49**	**42.99**	**42.97**	**43.83**	14.87
H_2O	**69.47**	**73.38**	17.72	18.61	17.43	23.59	16.82	5.71
CH_4	2×10^{-7}	2×10^{-8}	8×10^{-11}	0.74	0.66	0.39	0.71	0.17
CO_2	19.39	18.66	**70.54**	3.98	5.08	5.51	4.66	9.91
CO	3.15	1.79	2.45	26.87	32.51	26.06	31.47	**67.00**
N_2	0.82	0.57	0.01	0.37	0.33	0.29	1.31	1.85
NH_3	5×10^{-6}	2×10^{-6}	8×10^{-9}	0.01	0.01	9×10^{-5}	0.02	5×10^{-5}
H_2S	2.47	2.32	0.56	0.59	0.61	0.74	0.53	0.18
SO_2	0.08	0.35	7.41	1×10^{-8}	1×10^{-8}	3×10^{-8}	1×10^{-8}	1×10^{-8}
Other[a]	0.25	0.17	1.02	0.33	0.35	0.41	0.64	0.29
Total	99.99	99.96	99.95	99.99	99.97	99.96	99.99	99.98

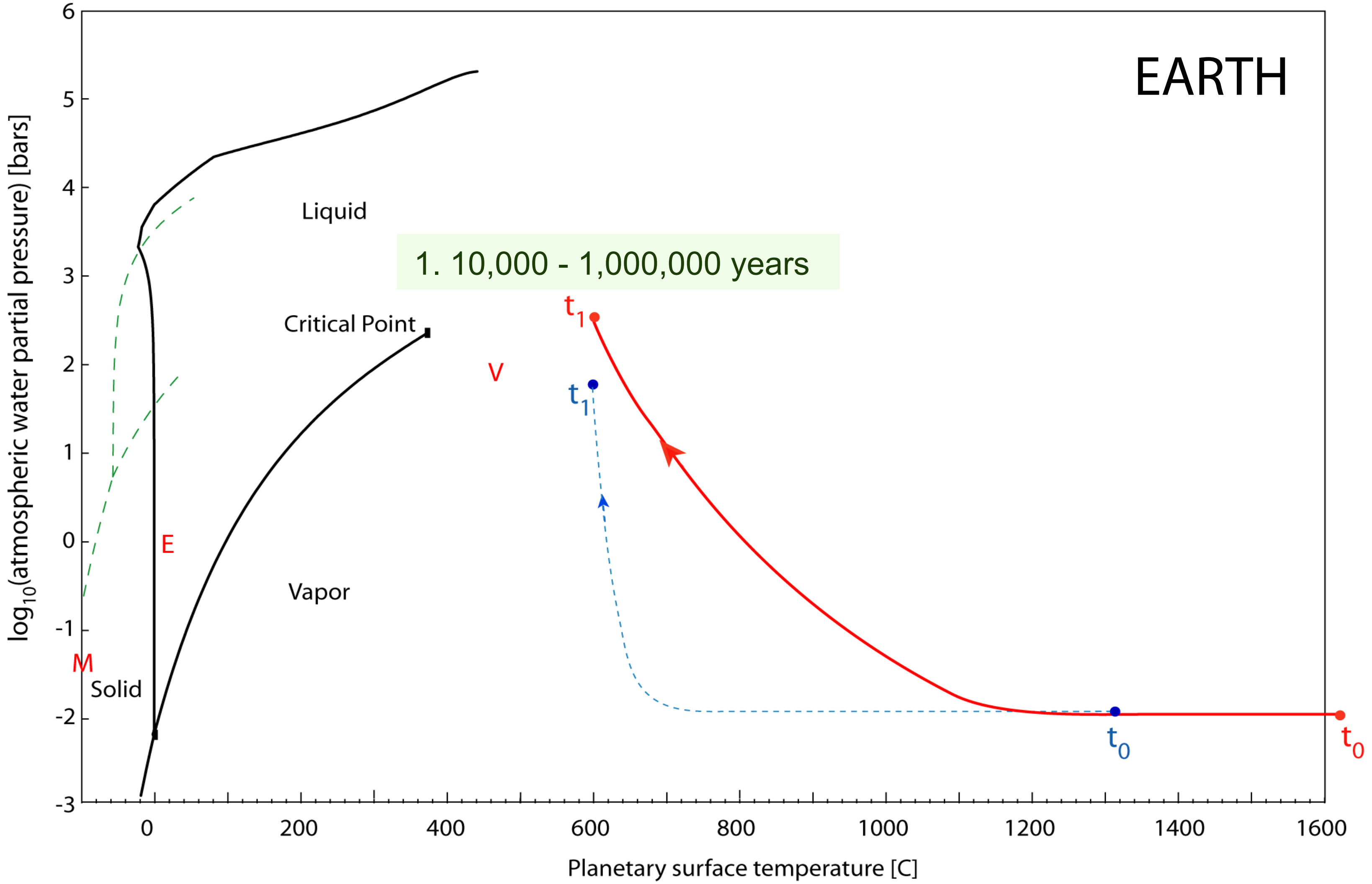
[a] Other includes gases of the rock-forming elements Cl, F, K, Na, P, and S. See text.

Schaefer and Fegley (2010)

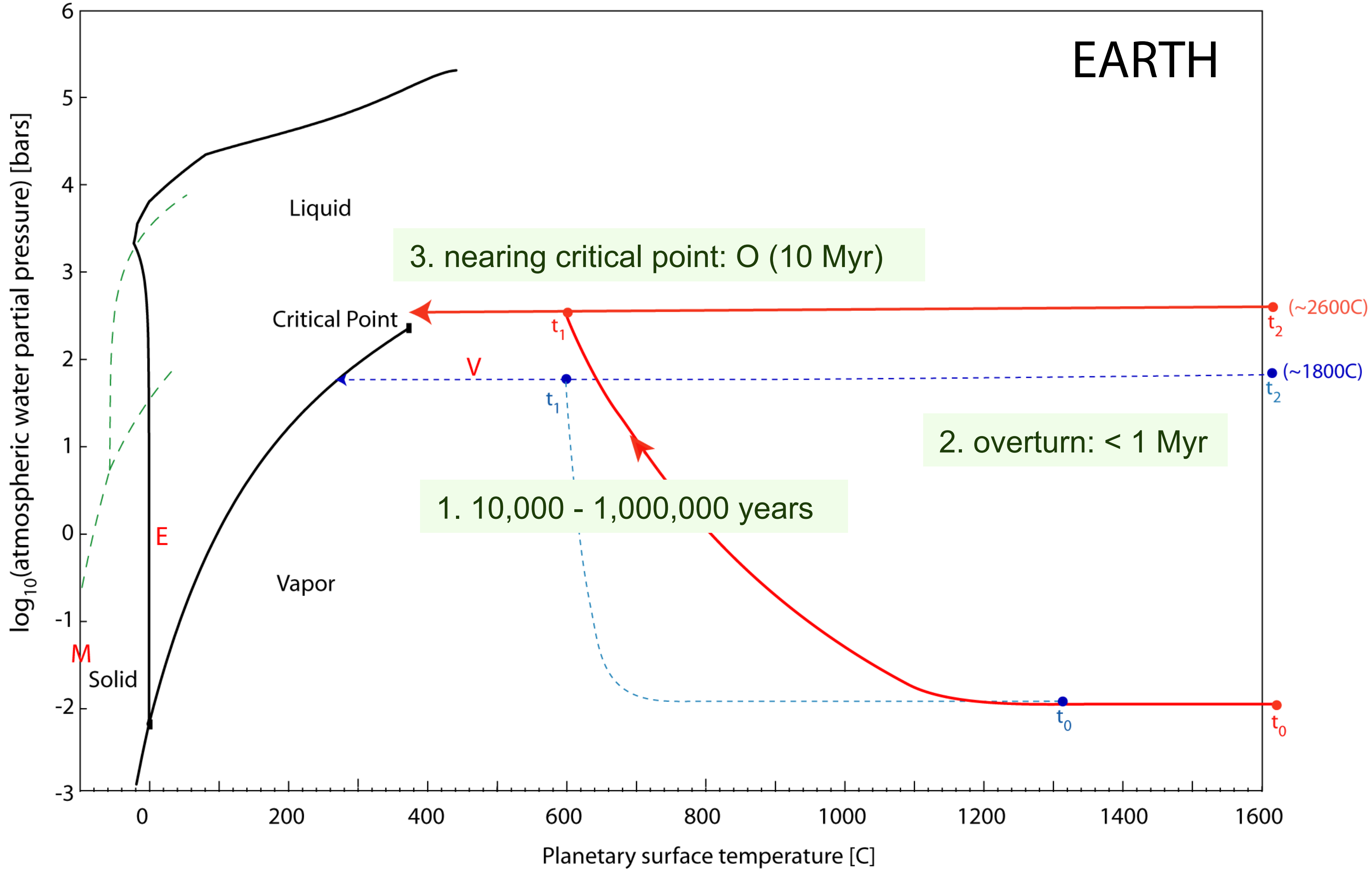
Paradoxical elements

- Nitrogen
  - Compatible with source from comets
    ($^{15}N/^{14}N$ and D/H; *e.g.* Mahaffey 2000; Owen, 2007; Hutsemékers et al. 2009)
  - But <~10% of water is from comets
    (*e.g.* Balsiger et al., 1995; Eberhardt et al., 1995; Bockelée-Morvan, 1998; Meier et al., 1998; Hutsemékers et al., 2008)

- Helium and other noble gases, Hydrogen



Elkins-Tanton (2008)

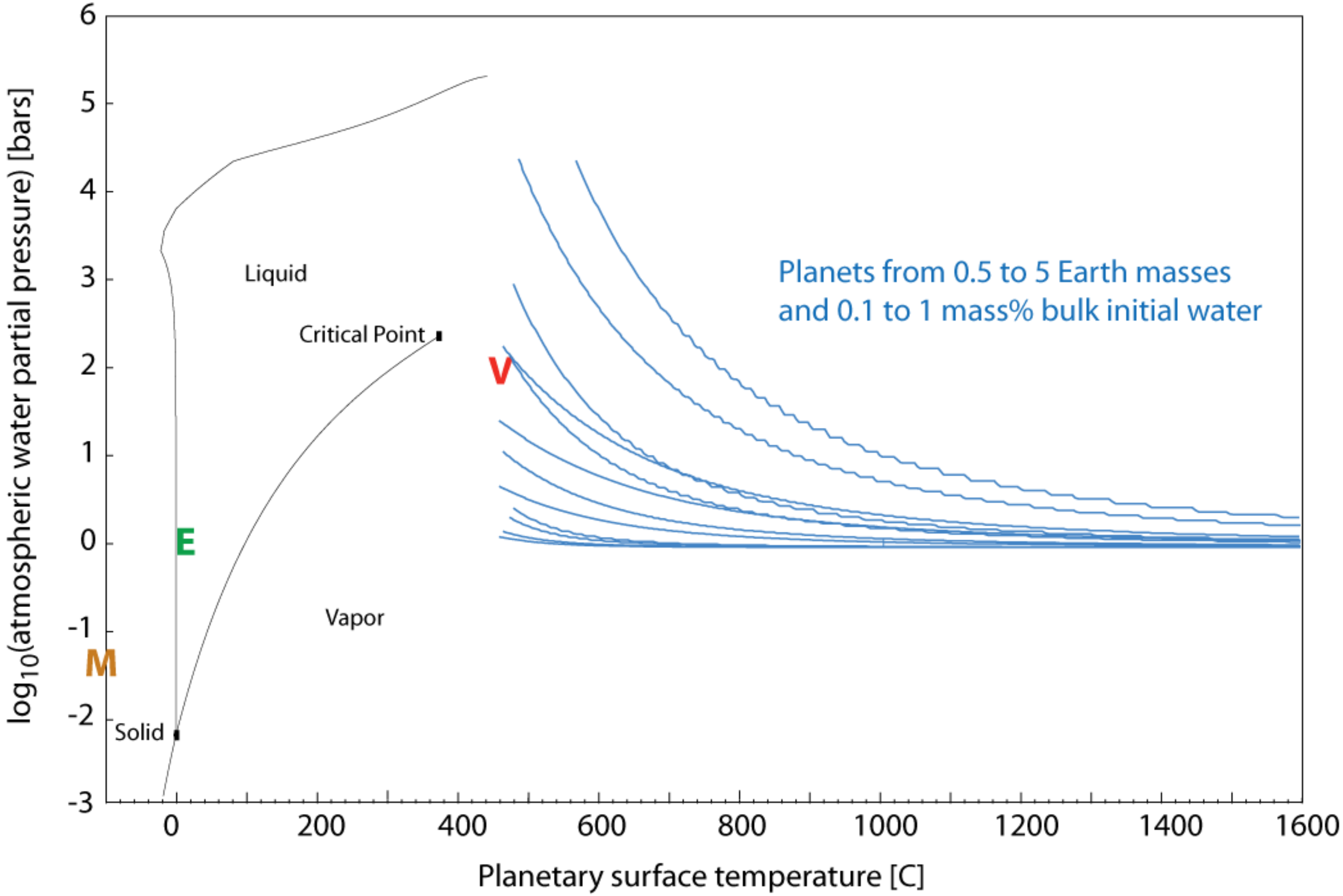


Elkins-Tanton (2008)

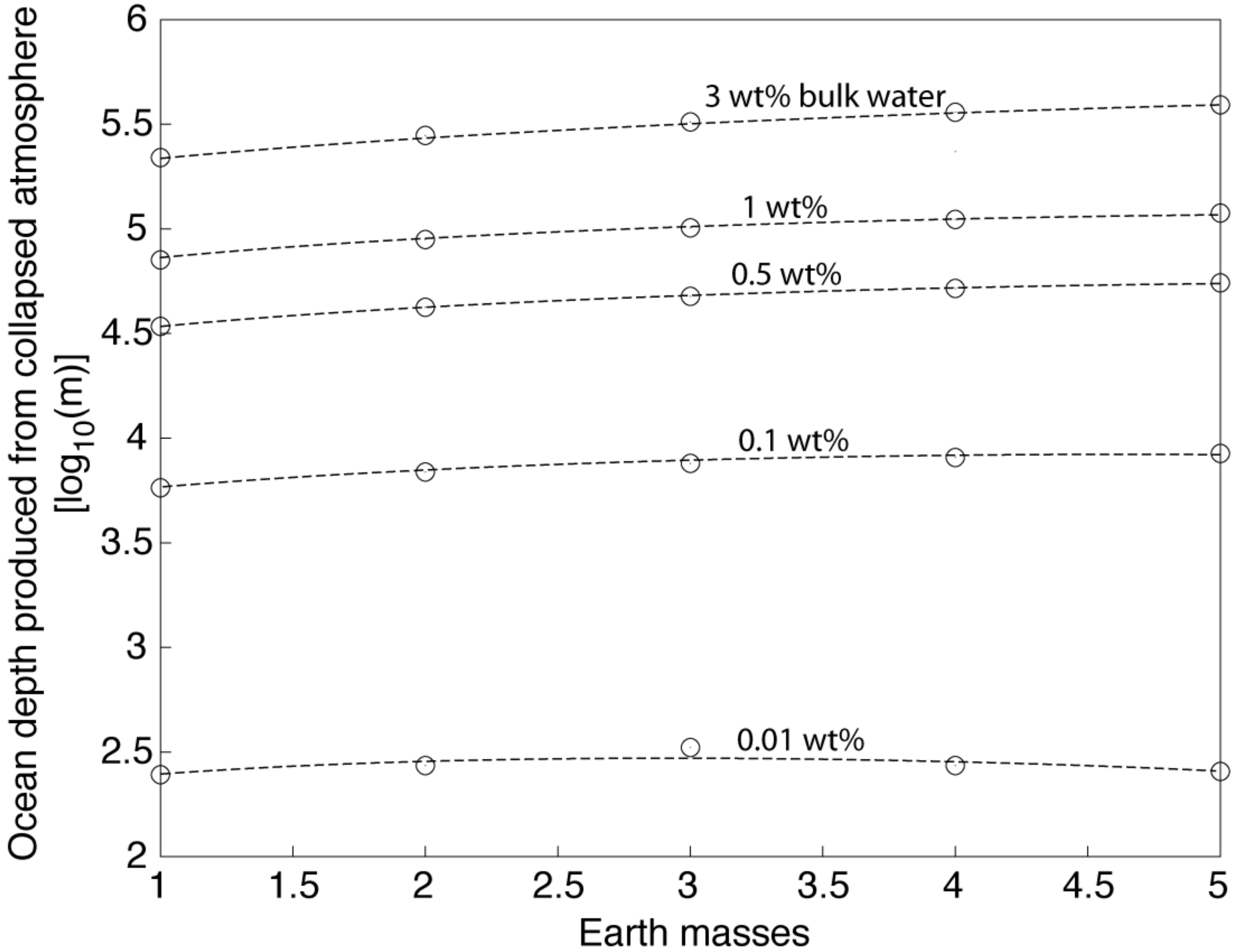
Life (1952)

New York Times (2008)

P-T paths of planetary surfaces during magma ocean solidification

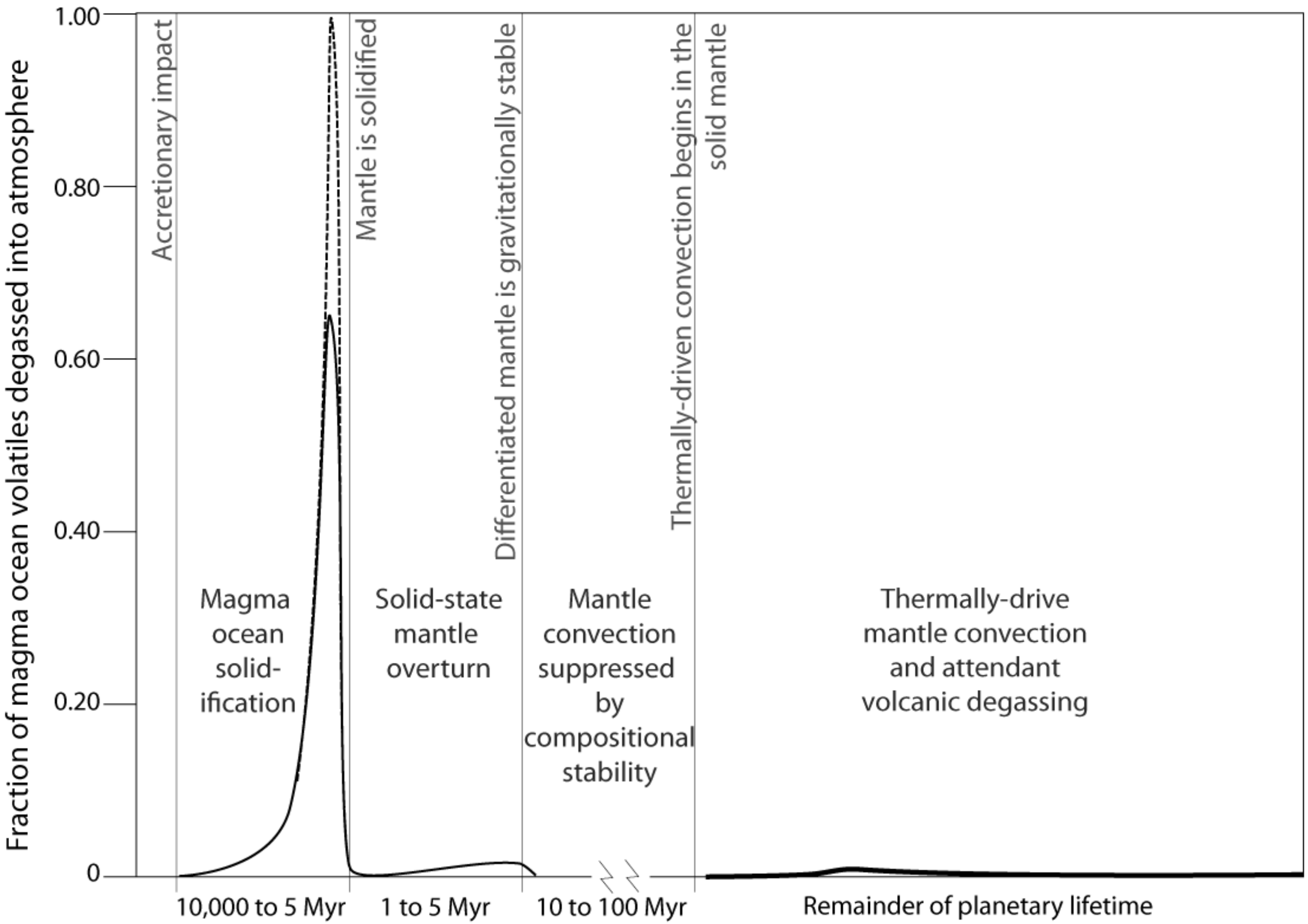


Elkins-Tanton (unpub.)

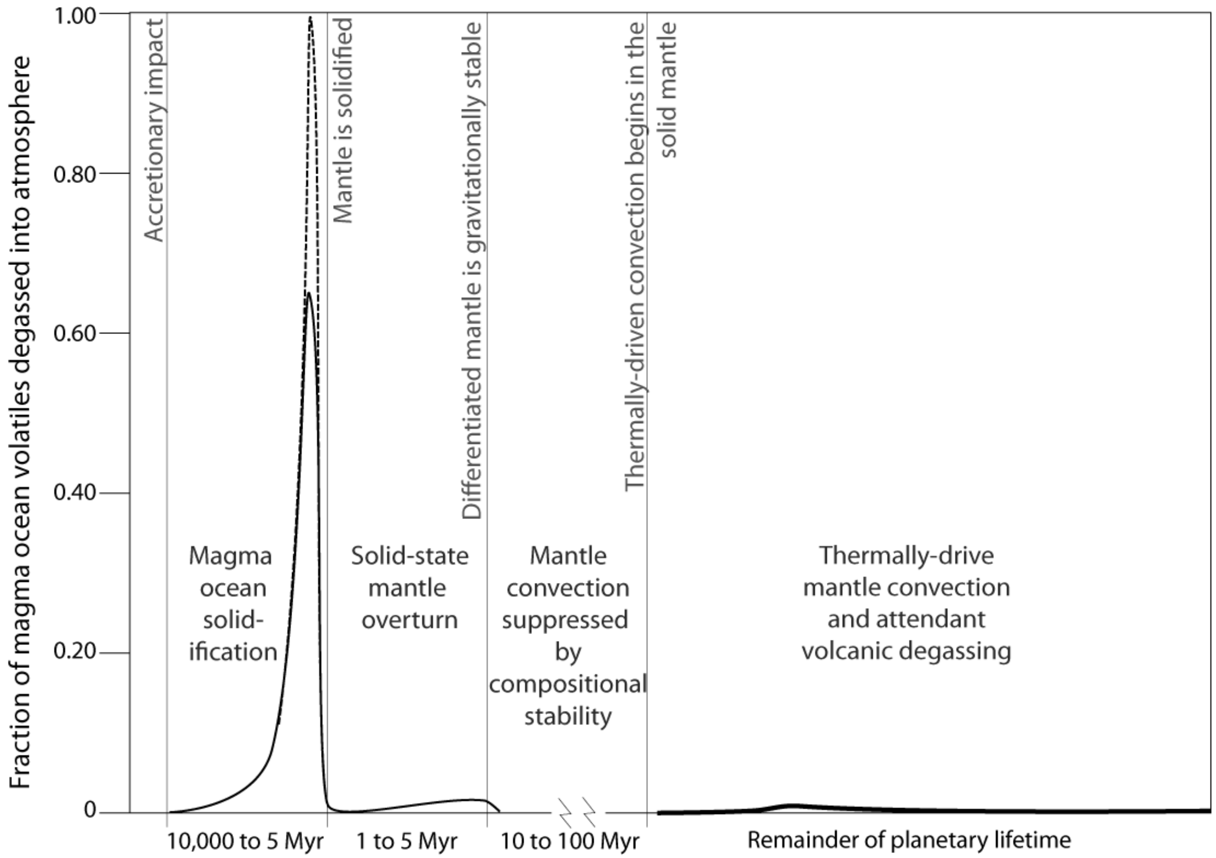


Elkins-Tanton (submitted)

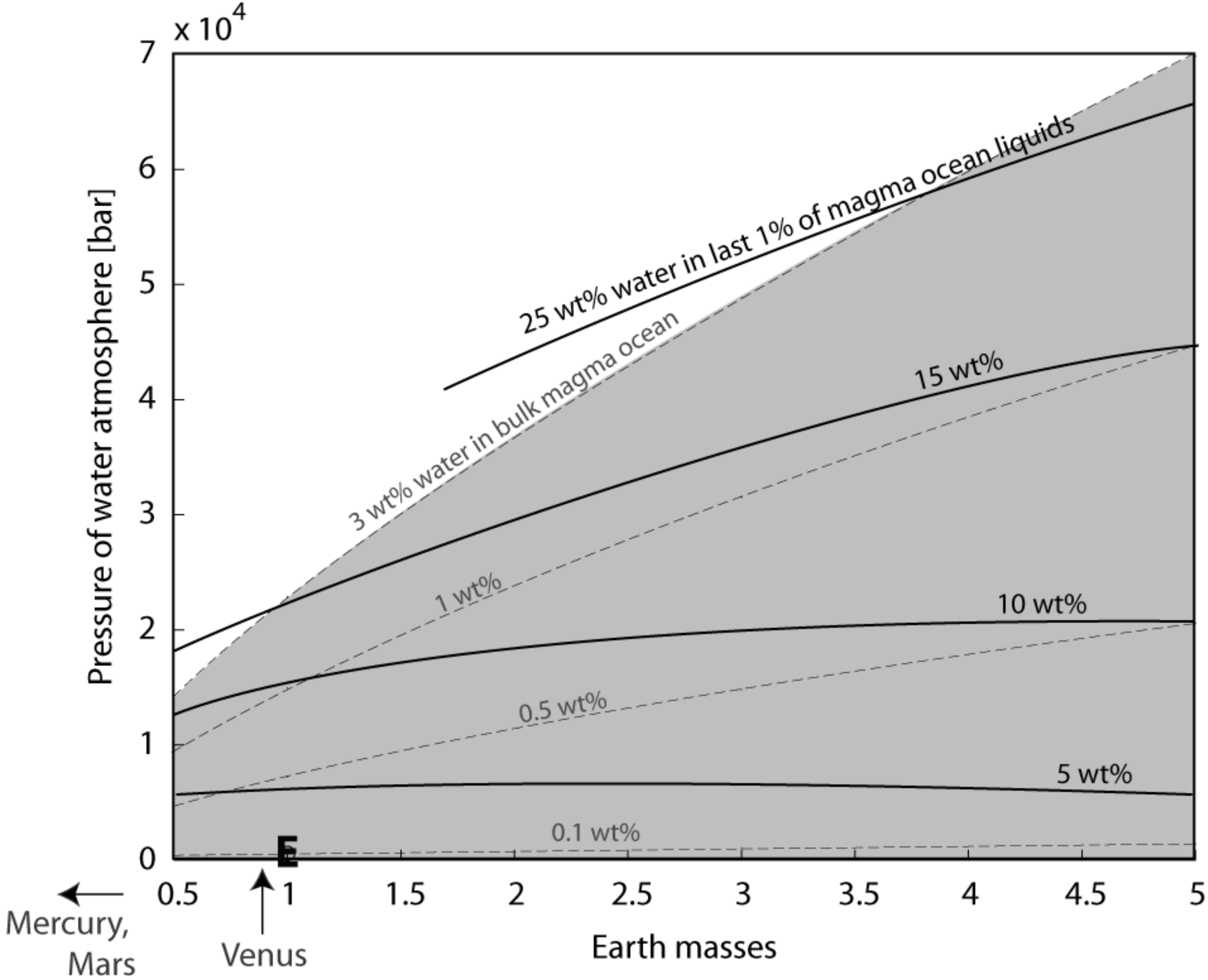
Atmospheric degassing timeline



Elkins-Tanton (submitted)

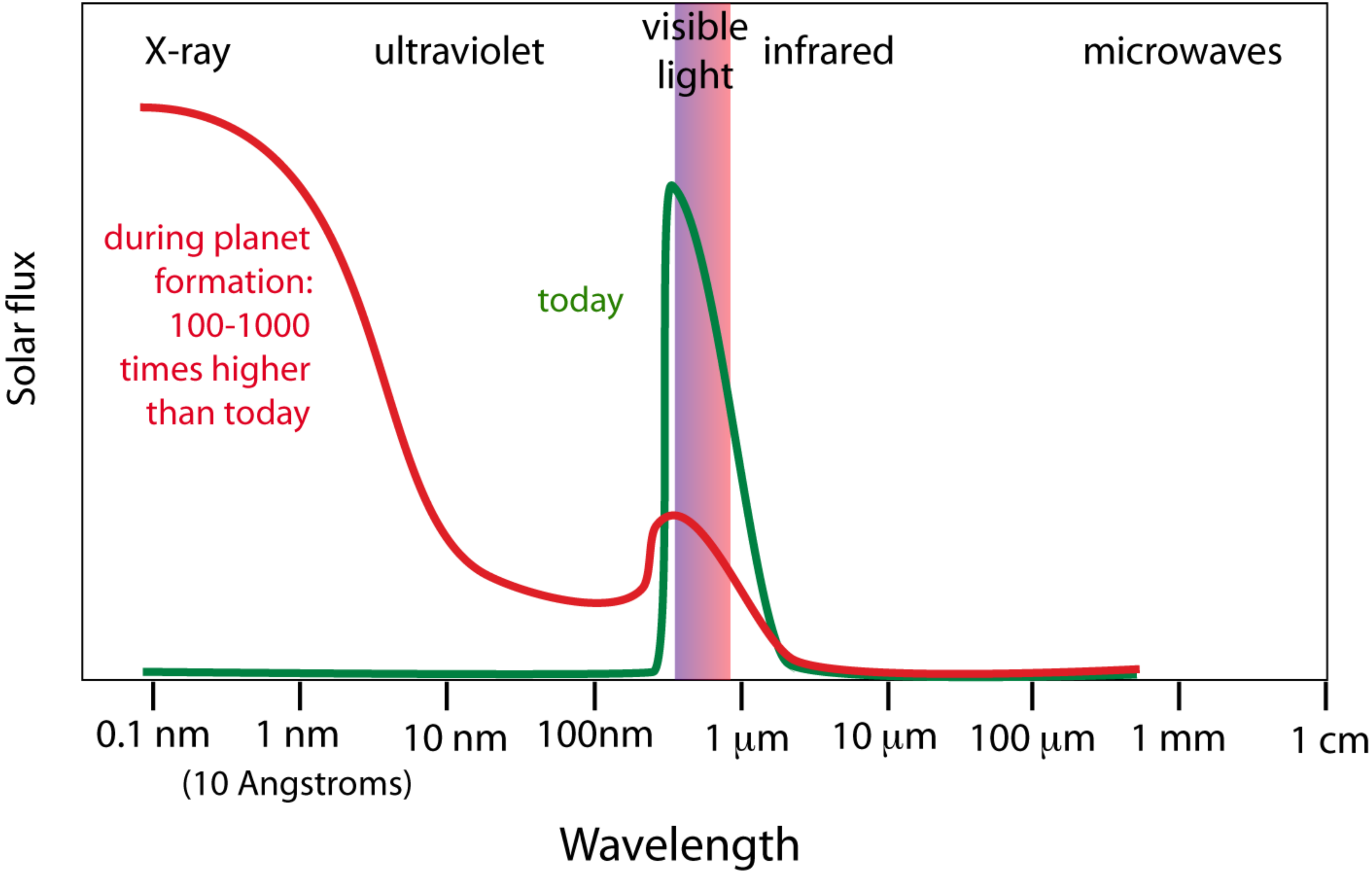


Fraction of magma ocean volatiles degassed into atmosphere
1.00
0.80
0.60
0.40
0.20
0
Accretionary impact
Mantle is solidified
Differentiated mantle is gravitationally stable
Thermally-driven convection begins in the solid mantle
Magma ocean solid-ification
Solid-state mantle overturn
Mantle convection suppressed by compositional stability
Thermally-drive mantle convection and attendant volcanic degassing
10,000 to 5 Myr
1 to 5 Myr
10 to 100 Myr
Remainder of planetary lifetime



Elkins-Tanton (submitted)

Atmospheric loss from high-radiation young Sun



Young Sun data from Ribas et al. (2005)

Faint young Sun: Hoyle (1958); Schwarzschild (1958); Sagan and Mullen (1972)

Varying initial volatile mix: Bars of atmosphere on Mars

Decreasing water, increasing carbon dioxide