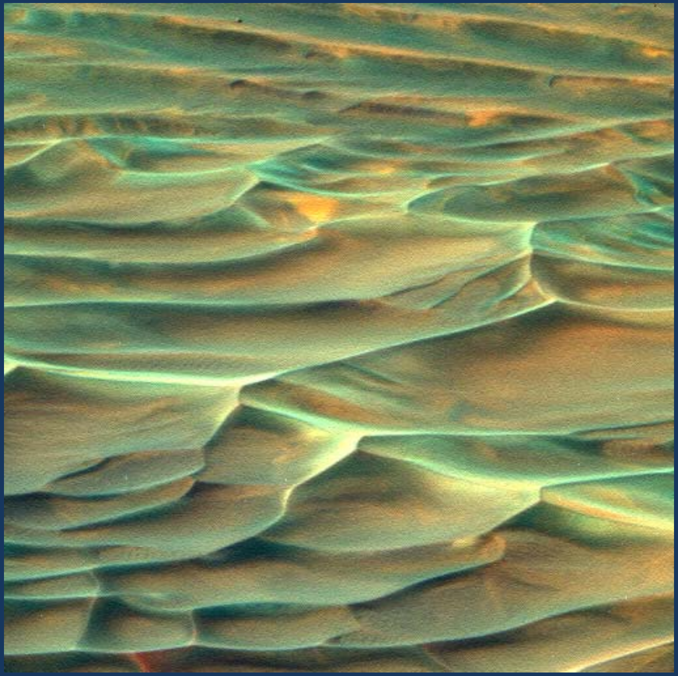
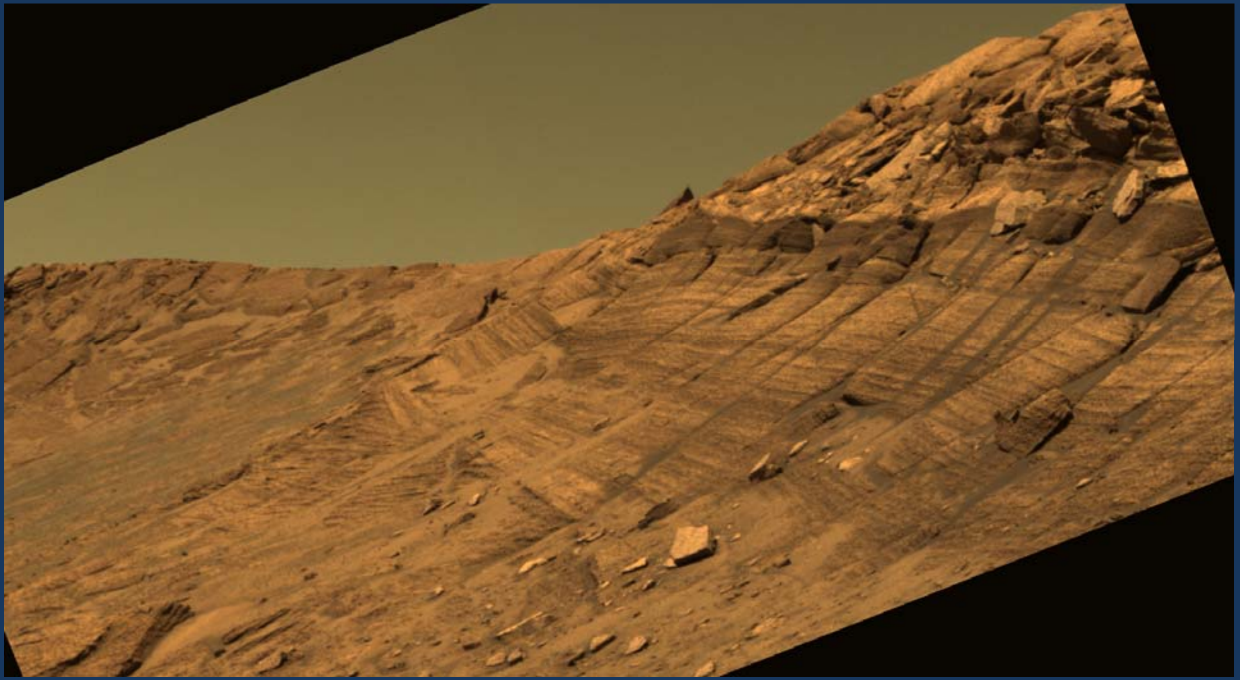
The Martian Sedimentary Mass: Constraints on its Composition, Age and Size

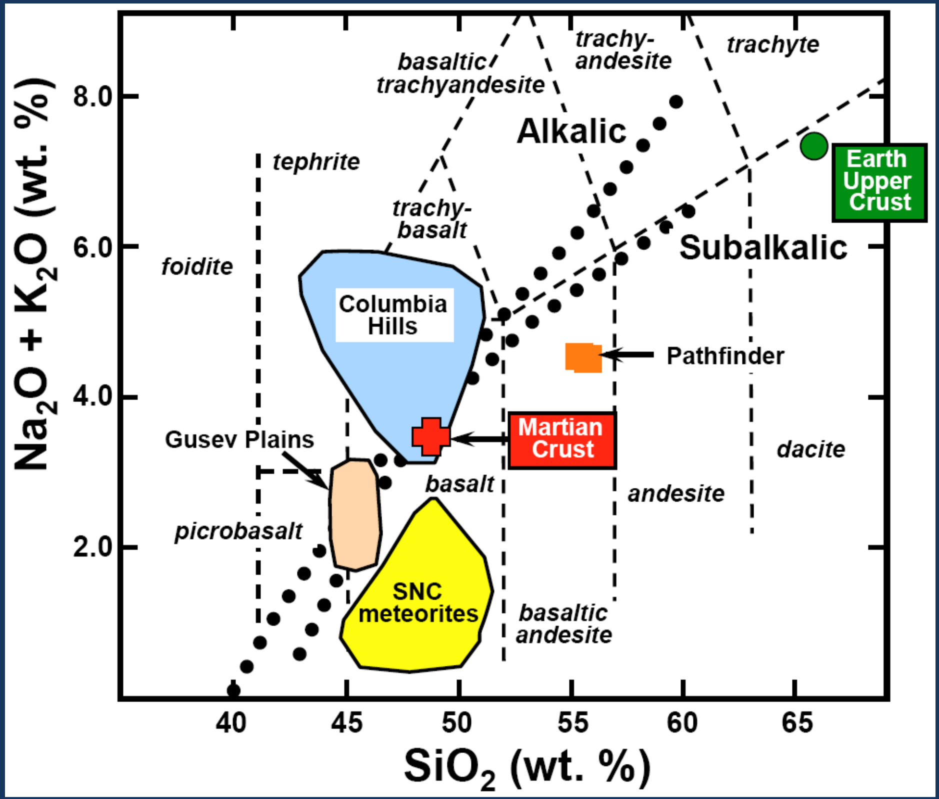
Scott McLennan

Department of Geosciences, SUNY Stony Brook





Martian Crustal Chemistry & Mineralogy



Taylor & McLennan (2009)

Mars Crust		Earth Upper Crust
17	Olivine	0
22	Pyroxene	1
10	Fe-Ti Oxides	1
22	Glass	13
29	Plagioclase	35
0	K-Feldspar	11
0	Sheet Silicates	14
0	Quartz	20

McLennan & Grotzinger (2008)

SEDIMENTARY MINERALOGY

Earth		Mars
	Phyllosilicates	
illite (K) smectite (Ca,Na,Mg) kaolinite		montmorillonite (Mg) nontronite (Fe,Mg) kaolinite
	Carbonates	
$CaCO_3$ $(Ca,Mg)CO_3$		$CaCO_3$ $MgCO_3$
	Sulfates	
$CaSO_4$		$MgSO_4$ $Fe^{2+}Fe^{3+}_2(SO_4)_4$ $CaSO_4$
	Iron Oxides	
Fe_2O_3 Fe_3O_4		Fe_2O_3
	Silica	
Opal-A ➔ Chert		Opal-A

SEDIMENTARY MINERALOGY

Earth | **Mars**

Phyllosilicates

Earth:
illite (K)
smectite (Ca,Na,Mg)
kaolinite

Mars:
montmorillonite (Mg)

Carbonates

Earth:
$CaCO_3$
$(Ca,Mg)CO_3$

Mars:
$CaCO_3$
$MgCO_3$

Sulfates

Earth:
$CaSO_4$

Mars:
$MgSO_4$
$Fe^{2+}Fe^{3+}_2(SO_4)_4$
$CaSO_4$

Iron Oxides

Earth:
Fe_2O_3
Fe_3O_4

Mars:
Fe_2O_3

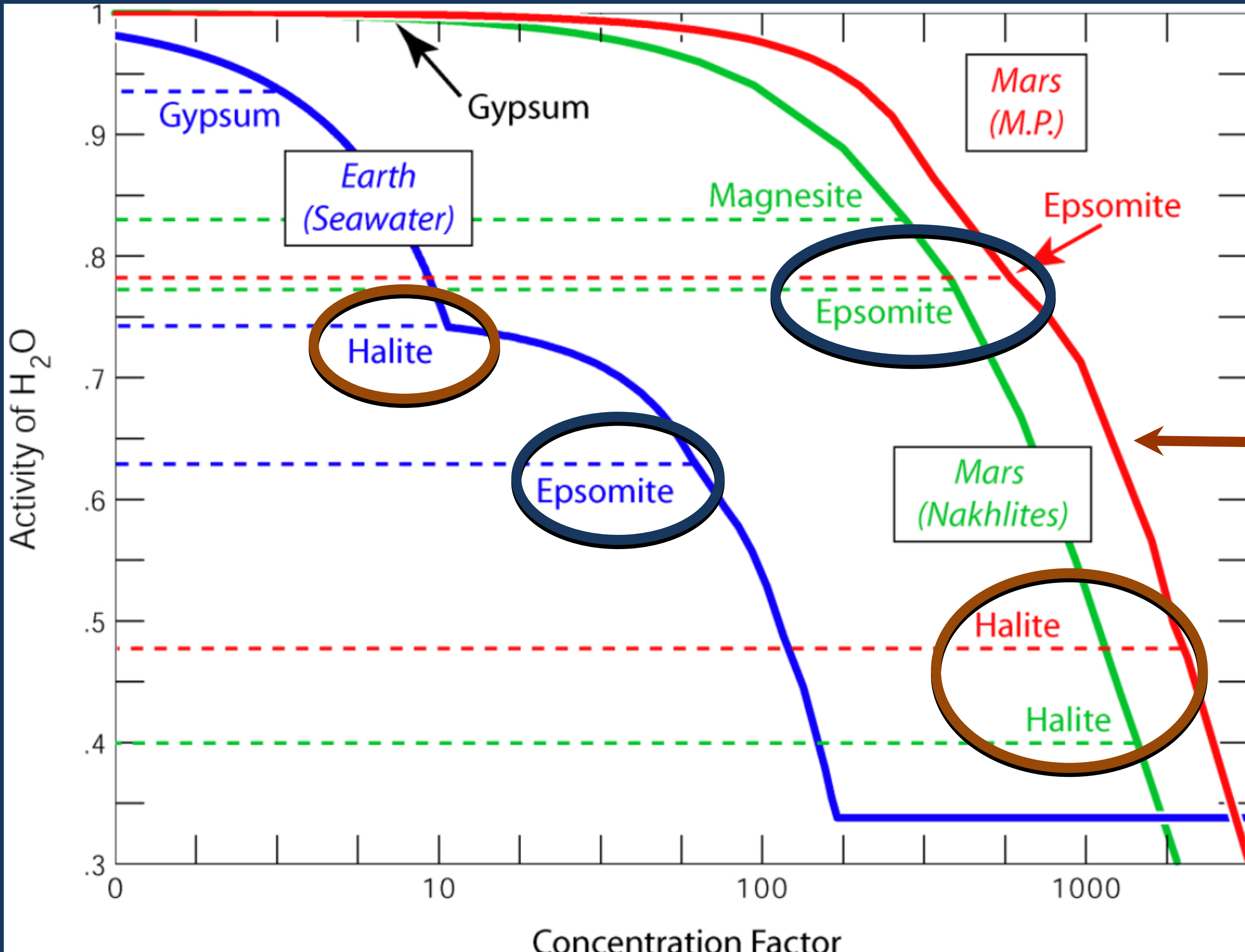
Silica

Earth:
Opal-A → Chert

Mars:
Opal-A

Martian sedimentary minerals Fe-Mg-rich & Na-K-poor compared to Earth reflecting basaltic provenance; "Immature" diagenetic assemblages

Evaporation Sequence

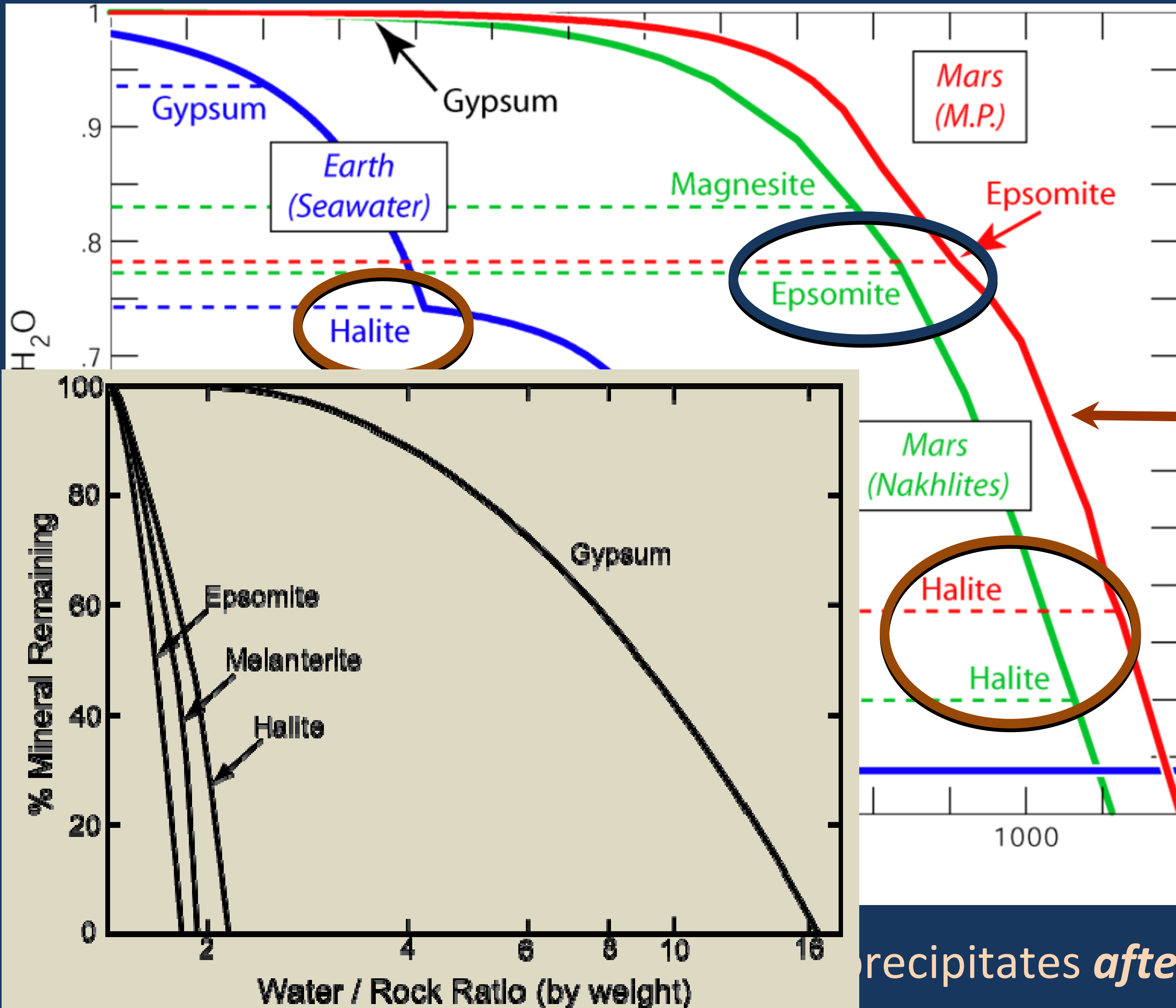


Limit to biological activity on Earth

Tosca et al. (2008)

In S-rich Martian basaltic brines halite precipitates ***after*** Mg-sulfates

Evaporation Sequence

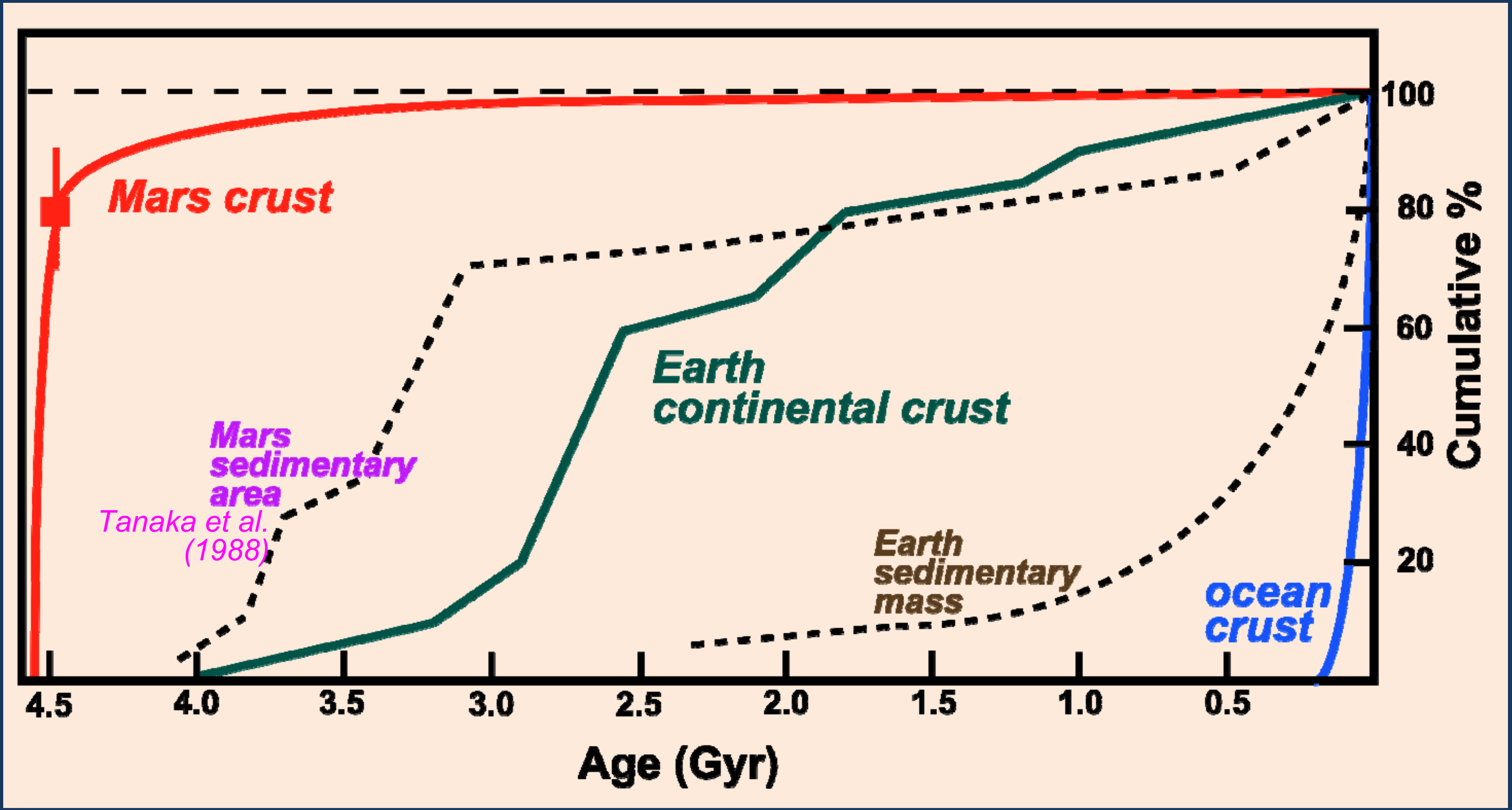


Limit to biological activity on Earth

Tosca et al. (2008)

recipitates ***after*** Mg-sulfates

Crustal & Sedimentary Evolution

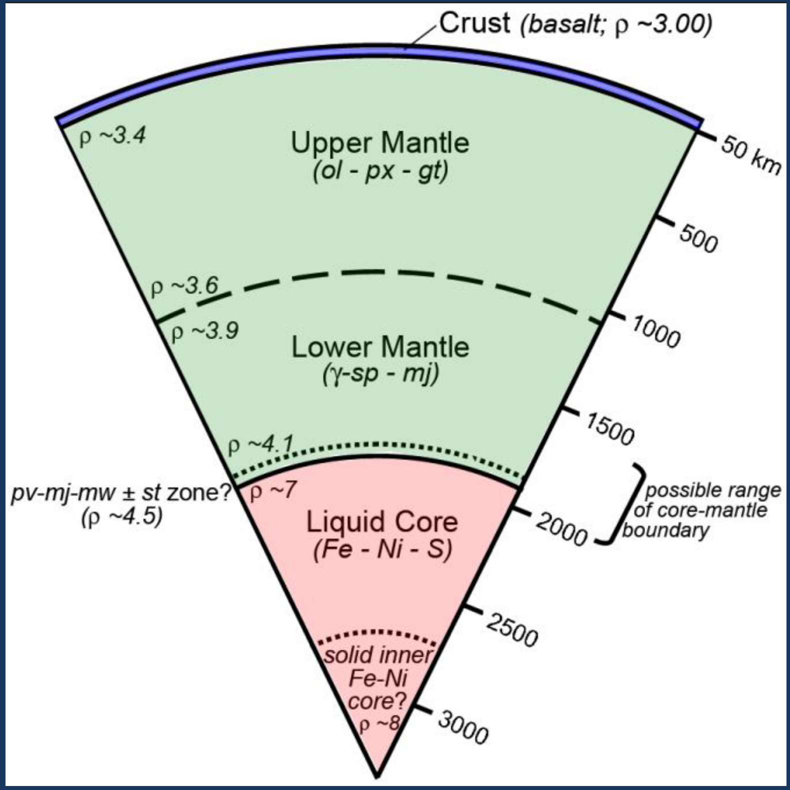


adapted from Taylor & McLennan (2009)

How Large is the Martian Sedimentary Record?

- for comparison, terrestrial sedimentary record is 2.7×10^{24}g
- direct measure from Martian stratigraphic records (as done on Earth) not possible
- indirect estimate from sulfur degassing history

Mars is a S-rich planet with crustal/mantle sulfur ~2× terrestrial levels



__Crust__
S ~ 2,000 ppm
(4.3×10^{22} g)

__Primitive Mantle__
S > 400 ppm
(> 2.1×10^{23} g)

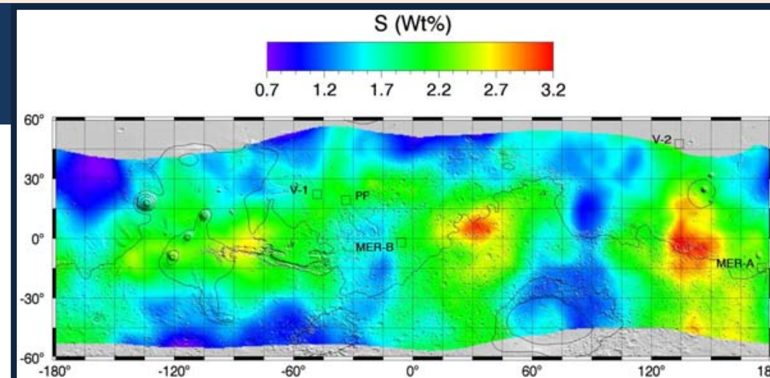
__Core__
S ~ 14%

Ancient Sulfur Cycle on Mars

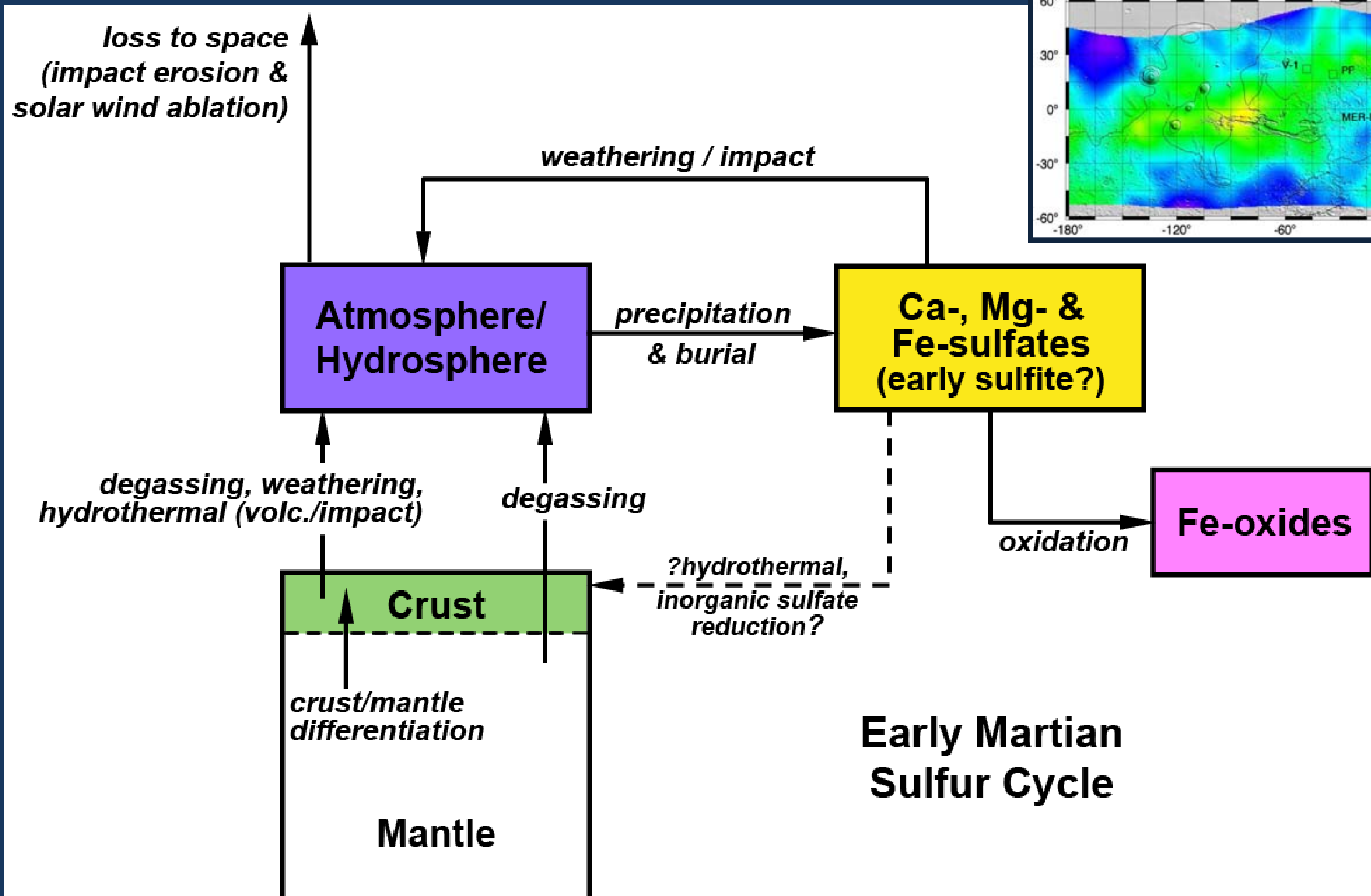
Mineral Epoch	Phyllosian	Theiikian	Siderikian
Mineralogy	*Clay-rich*	*Sulfate-rich*	*Anhydrous Ferric Oxide-rich*
Environment	*circum-neutral pH water-rich*	*low pH water-limited?*	*low pH water-limited*
Age	Noachian	Hesperian	Amazonian

~4.5Gyr ~3.7Gyr ~3.0Gyr 0 Gyr

Bibring et al., 2006

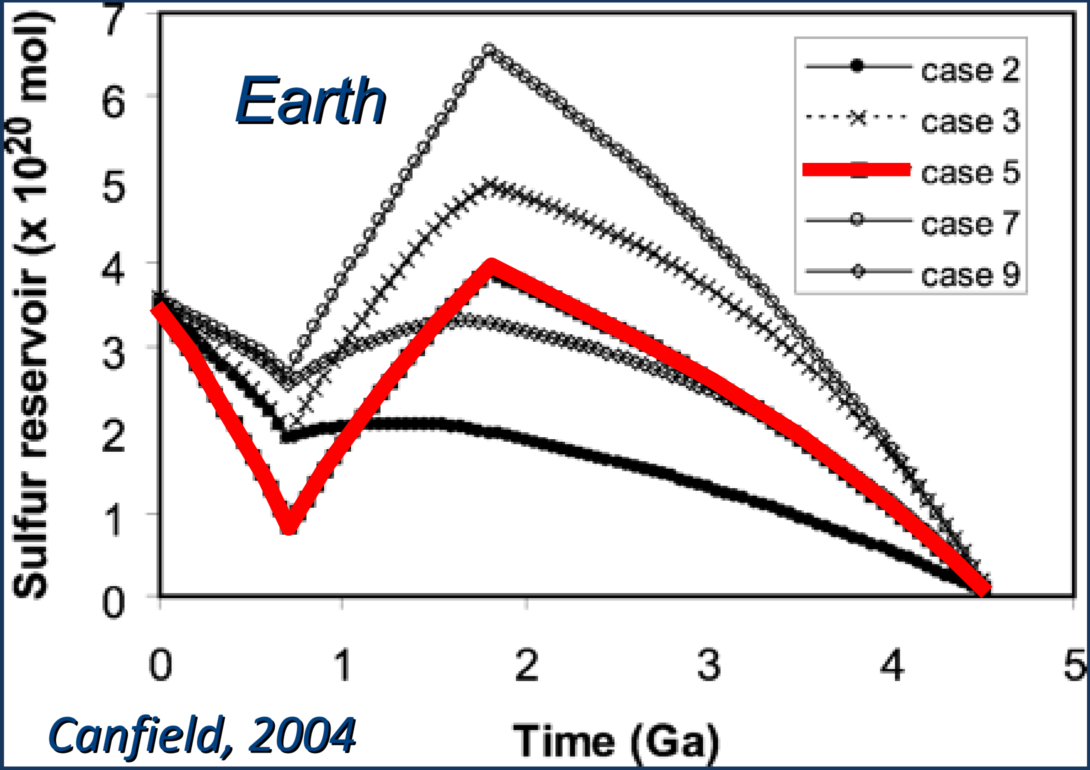


King & McLennan, 2010



Sulfur Outgassing on Earth

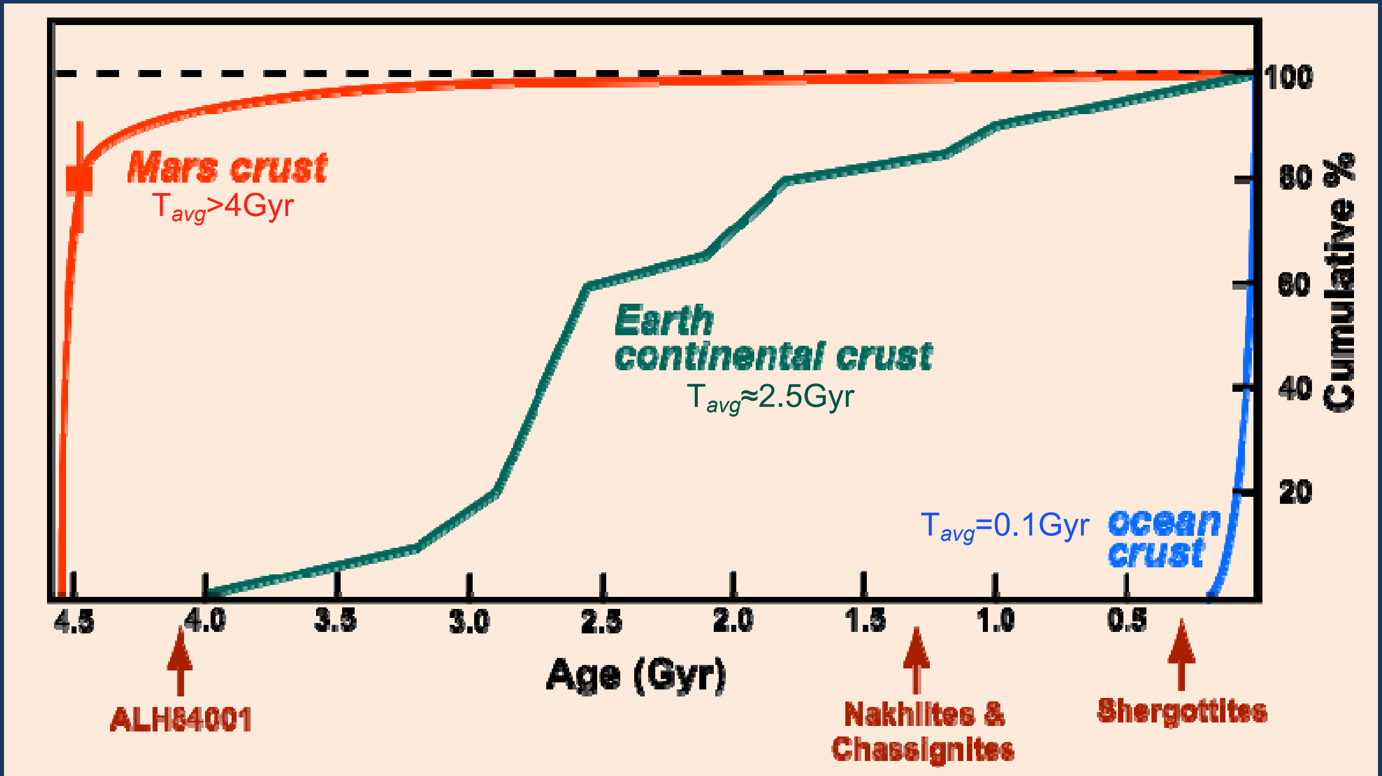
- estimated size of Earth's outgassed S reservoir is model dependent
- Terrestrial history complicated by S loss from crust-mantle recycling (i,.e., plate tectonics)
- estimate integrated total S through surface reservoir
- for modest assumptions
  - integrated over time ~1.1×10^{23} g
  - 11% of Earth's primitive mantle sulfur



Canfield, 2004

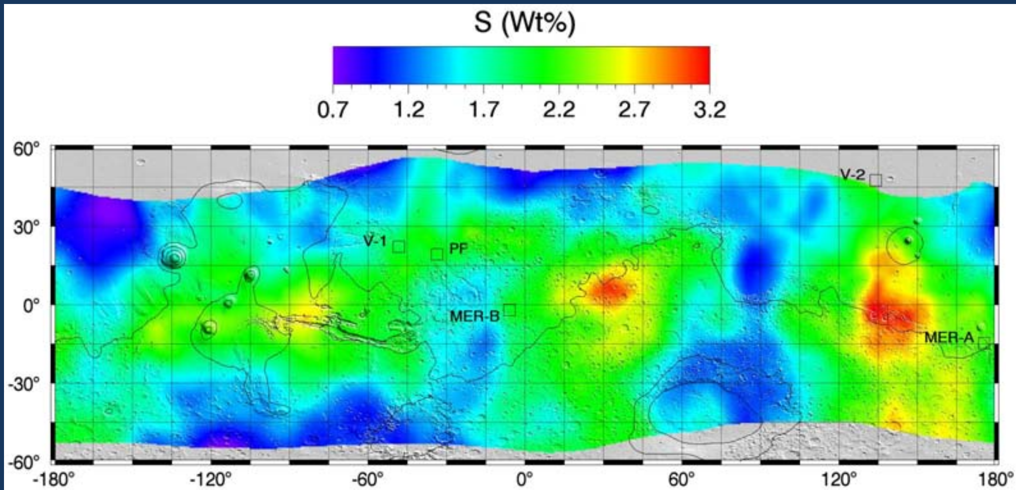
Sulfur Outgassing on Mars - 1

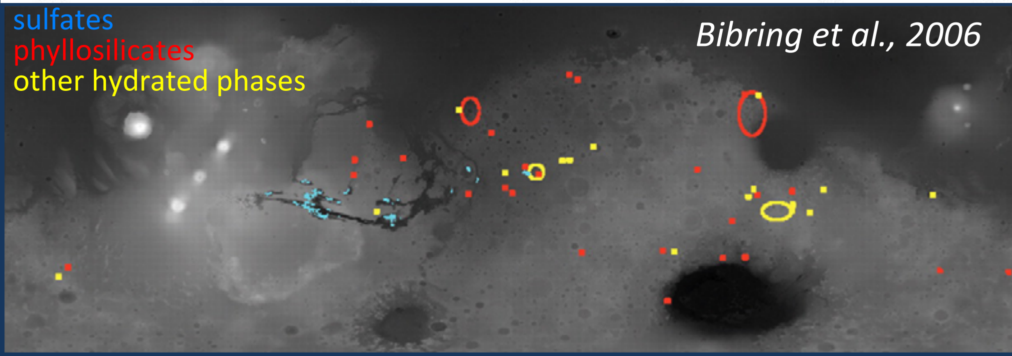
- Mars differentiated much earlier than Earth
- ≥50% differentiation of Mars primitive mantle versus ~25-30% for terrestrial mantle (and S is an incompatible element)
- no plate tectonics - no mantle recycling – what comes to the surface stays on the surface



Sulfur Outgassing on Mars -2

- assume 11% S outgassing – likely a lower limit
- adopt 400 ppm S in primitive mantle – also likely a lower limit
- Martian near-surface S reservoir:
  - ~2.3×10^{22} g from S outgassing
  - ~2× current Earth value but ~20% integrated value
  - ~2-3km with average GRS/soil composition
  - estimates from magmatic history ~4-10× lower but all lower limits
  - ≥ 10^{21} – 10^{22} g Sulfur





Bibring et al., 2006

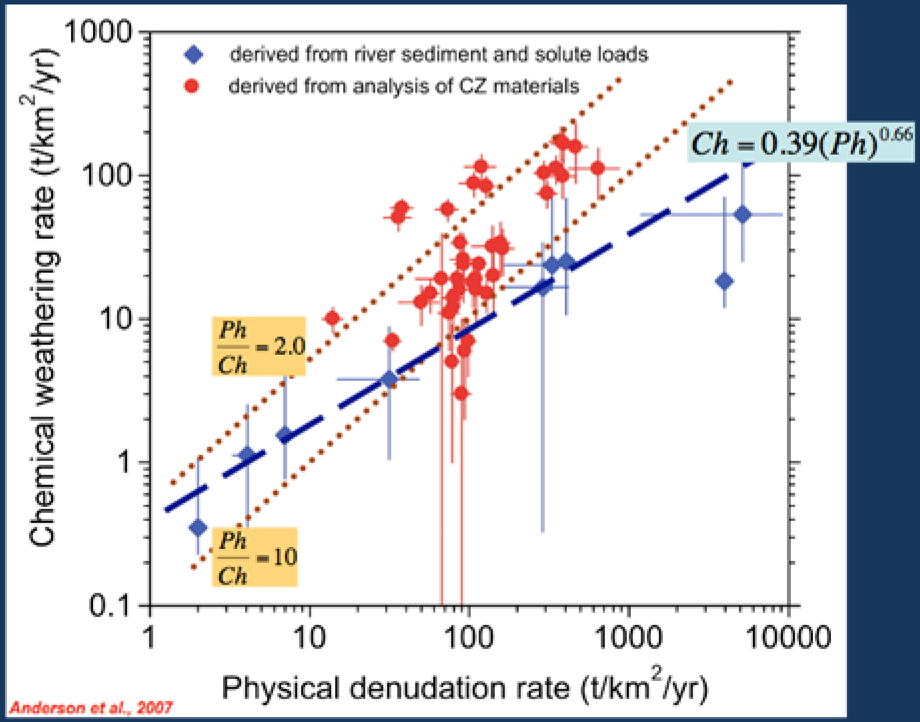
Martian Sedimentary Mass -1

- For calculation, adopt lower S value of 10^{21} g
- Chemical Sedimentary Mass:
  - For ***sulfates*** assume crustal cation proportions – $Fe_{0.4}Mg_{0.4}Ca_{0.2}SO_4{\bullet}2H_2O$ — 5.5×10^{21} g
  - For ***chlorides*** assume soil S/Cl ratio (3.6) and 50:50 mix – NaCl : $Mg_{0.67}Ca_{0.33}Cl_2$ — 2×10^{20} g
  - Assume negligible ***carbonates*** — --
  - For ***sedimentary silica*** assume one mole silica for each mole of sulfate and chloride – $SiO_2{\bullet}1.5H_2O$ — 2×10^{21} g

- **Total Chemical Sedimentary Mass:** 8×10^{21} g

Martian Sedimentary Mass -2

- Ratio between clastic (*Ph*) & chemical (*Ch*) constituents studied on Earth – estimates for total sedimentary mass range from ***3:1*** to ***6.5:1***
- Ratio likely higher on Mars – greater role for impacts and pyroclastics providing particulates
- Assume *Ph/Ch = 5*
- Indicates Martian sedimentary mass ***5X10^{22} g*** for 10^{21} g S and ***5X10^{23} g*** for 10^{22} g S



- **Martian sedimentary mass is *≥ 2% - 20%* terrestrial sedimentary mass**

Some Conclusions

- Martian sedimentary record has distinctive chemical and mineralogical character compared to Earth due to basaltic crust:
    - *chemical and clastic minerals and sedimentary rock fragments are Fe-Mg-rich*
    - *chemical precipitation pathways differ (e.g., evaporative minerals and evaporation sequences)*

- Martian sedimentary mass much older than terrestrial sediments due to early formed crust and probable distinctive sedimentary recycling history

- Assuming degassed sulfur reacts to form chemical mineralogical constituents, it it possible to estimate the overall Martian sedimentary mass
    - $\geq 5\times10^{22} - 5\times10^{23}$ *g*
    - *≥ 2 - 20 % of the size of the terrestrial sedimentary mass*