[AV]Origins and Cycling of CO_2 from Earth during the Archean and Proterozoic Eons*

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Abstract

Earth acquired essentially its entire carbon inventory very early. Most carbon arrived as volatile components trapped within planetesimals that formed the planet. As Earth approached its ultimate size, the greater energy associated with large impacts caused substantial amounts of volatiles to be lost to space. Because the redox state of the upper mantle has been relatively constant for at least the past 3.7 billion years, CO_2 and CO_3^{-2}species have dominated mantle carbon inventories since the early Archean. The cycling of carbon between its reservoirs in the atmosphere, ocean, crust, and mantle has responded to major long-term evolutionary trends; e.g., increasing solar luminosity, declining sizes and rates of impacts, declining radiogenic heat flow, and the stabilization of large continents. The major changes have occurred principally in the relative sizes of these carbon reservoirs and in the carbon fluxes that linked them. Today, rates of carbon exchange between the mantle and crust are slower (~10%) than global sedimentary carbon cycling which, in turn, is much slower (~0.1%) than global biological carbon cycling. The hotter Archean mantle must have influenced significantly the inventory of carbon in the crust, oceans, and atmosphere. Higher Archean rates of crustal production sustained higher mantle carbon outgassing rates. A hotter upper mantle retained any subducted carbon with greater difficulty. All of this indicates that the Archean crustal carbon inventory actually might have exceeded the modern crustal inventory. The enormous size of the mantle, together with more vigorous Archean mantle-crust exchange, probably allowed the mantle to control crustal volatile inventories and constrain the redox state of surface environments to a greater extent than it does today. This control weakened over time, following the decay of mantle radionuclides and declining heat flow. Also, the tectonic reworking of ancient crust during the Late Archean and Early Proterozoic led to more stable continents with more extensive stable shallow marine platforms that became major sites for the deposition and long-term preservation of carbonates and organic carbon. The rise of pervasive photosynthetic microbial communities transformed life into a major player in carbon cycling. Biological productivity enhanced sedimentary organic carbon burial rates; it contributed to the oxidation of the oceans and atmosphere, and ultimately it helped to modulate atmospheric CO_2 levels.

References

Delano, J.W., 2001, Redox history of the Earth's interior since approximately 3900 Ma; implications for prebiotic molecules: Origins of Life and Evolution of the Biosphere, v. 31/4-5, p. 311-341.

Des Marais, D.J., 2002, Biogeochemical carbon cycles during the Archean and early Proterozoic: Geochimica et Cosmochimica Acta, v. 66/15A, 178 p.

Des Marais, D.J., 2001, Isotopic evolution of the biogeochemical carbon cycle during the Precambrian; Reviews in Mineralogy and Geochemistry, v. 43, p. 555-578.

Des Marais, D.J., 2001, The Archean-Proterozoic transition; carbon isotopic indicators of change, p. 64-65.

Des Marais, D.J., 1984, Isotopically light carbon in midocean ridge basalts; fact or artifact?: Abstracts with Programs Geological Society of America, v. 16/6, p. 486-487.

Des Marais, D.J. and J.G. Moore, 1984, Carbon and its isotopes in mid-oceanic basaltic glasses: Earth and Planetary Science Letters, v. 69/1, p. 43-57.

Pepin, R.O., 1991, On the origin and early evolution of terrestrial planet atmospheres and meteorites volatiles: Icarus, v. 92/1, p. 2-79.

Resing, J., E.T. Baker, F. Martinez, G. Lebon, S. Walker, G.J. Massoth, B. Taylor, J.E. Lupton; R.R. Greene, K. Nakamura, J. Smith, 2004, Characteristics of hydrothermal activity in the Lau back arc basin: Eos Transactions American Geophysical Union, Suppl., v. 85/47, p, Abstract V44A-07.

Resing, J.A; J.E. Lupton, R.A. Feely, M.D. Lilley, 2004, CO (sub 2) and (super 3) He in hydrothermal plumes; implications for mid-ocean ridge CO (sub 2) flux: Earth and Planetary Science Letters, v. 226/3-4, p. 449-464.

Saal, A.E., E. Takazawa, F.A. Frey; N. Shimizu, S.R. Hart, 2001, Re-Os isotopes in the Horoman peridotite; evidence for refertilization?: Journal of Petrology, v. 42/1, p. 25-37.

Shields, G. and J. Veizer, 2002, Precambrian marine carbonate isotope database: Version 1.1.: Geochemistry Geophysics Geosystems, v.3/6, doi: 10.1029/2001GC000266.

Zahnle, K. and R.M. Haberle, 2007, Atmospheric sulfur chemistry on ancient Mars: LPI Contribution, Report # 1353, p. Abstract 3256.

Zahnle, K.J. and A. Colaprete, 2007, Secondary craters and the liberation of ice on Mars: LPI Contribution, Report # 1353, p. Abstract 3274.

Zahnle, K.J., J. Alvarellos, A. Dobrovolskis, P. Hamill, 2007, Primary, secondary, and sesquinary craters on Europa: LPI Contribution, Report # 1357, p.155-156.

Origins and Cycling of CO_2 on Earth During the Archean and Proterozoic Eons

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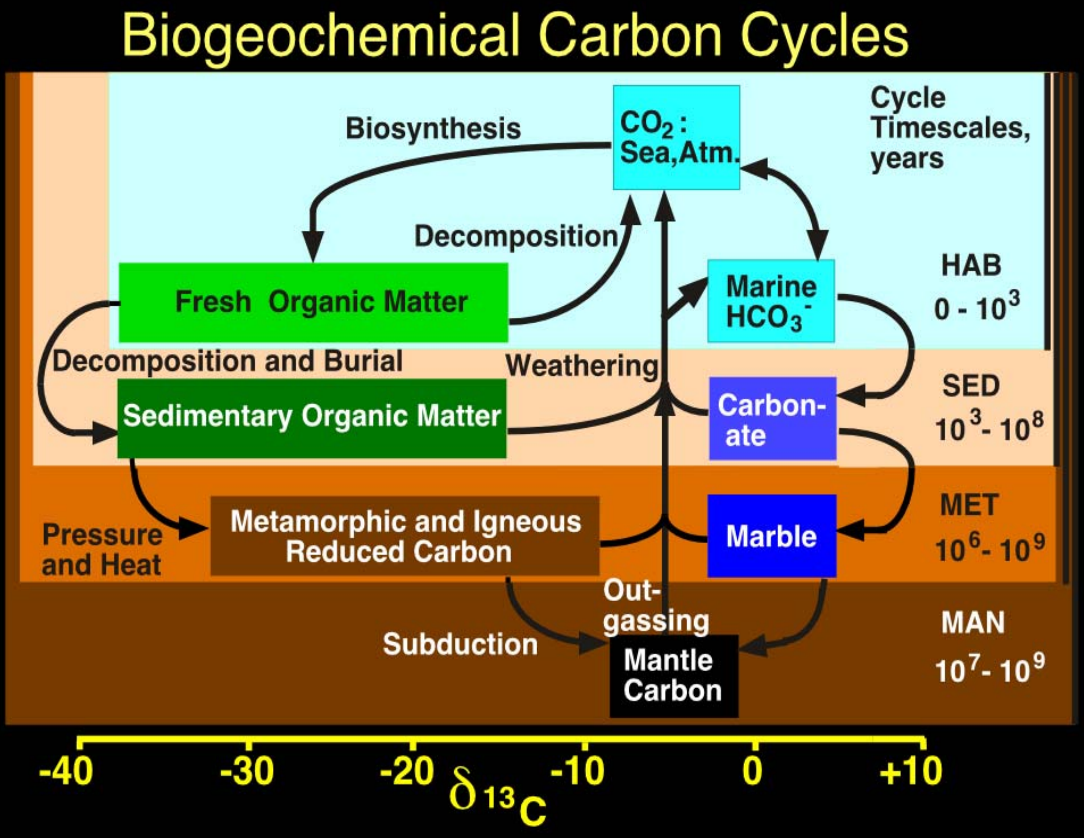
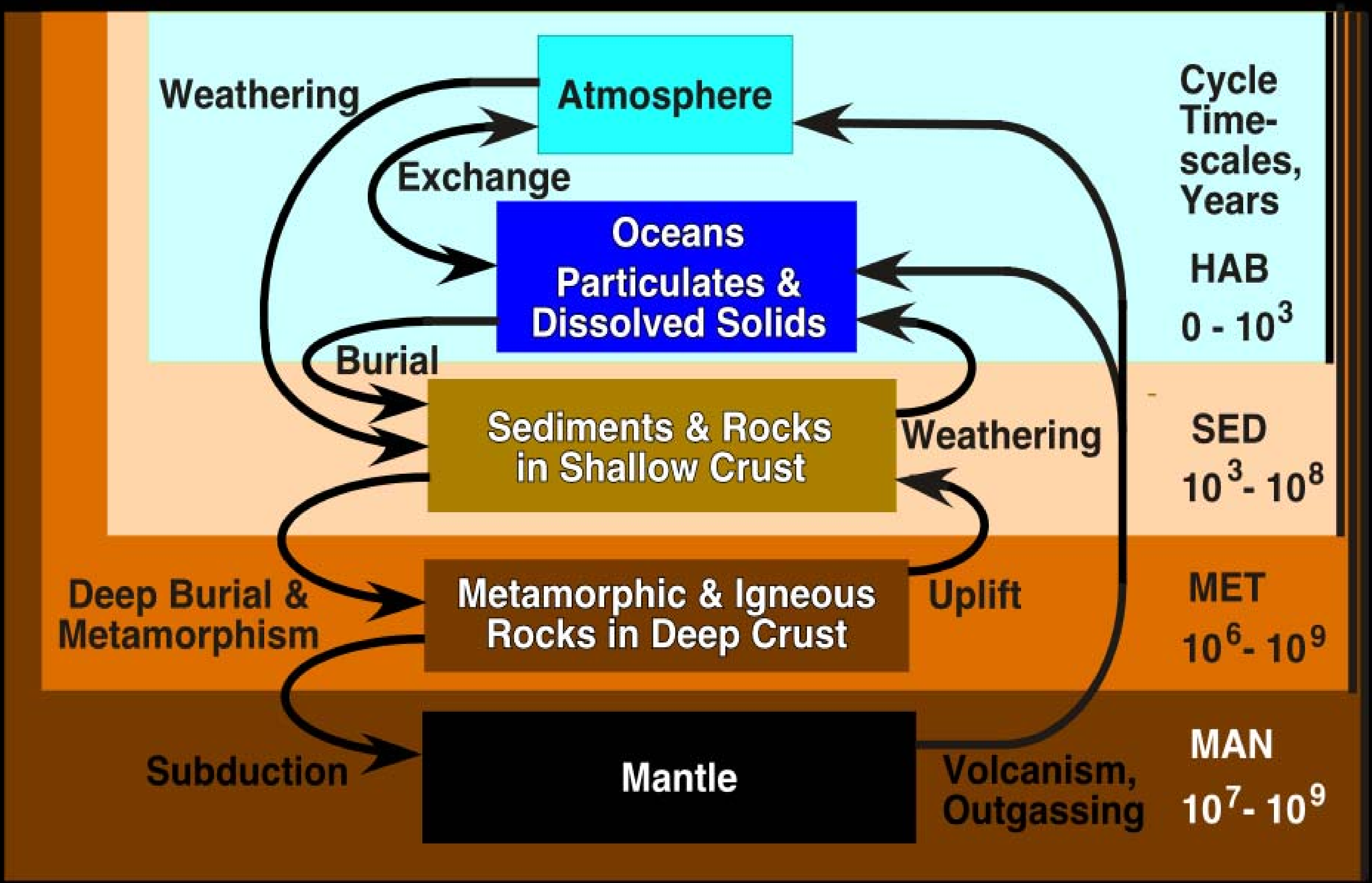


Biogeochemical Carbon Cycles

Geochemical Cycles



Weathering

Atmosphere

Exchange

Oceans
Particulates &
Dissolved Solids

Burial

Sediments & Rocks
in Shallow Crust

Weathering

Deep Burial &
Metamorphism

Metamorphic & Igneous
Rocks in Deep Crust

Uplift

Subduction

Mantle

Volcanism,
Outgassing

Cycle
Time-
scales,
Years

HAB
$0 - 10^3$

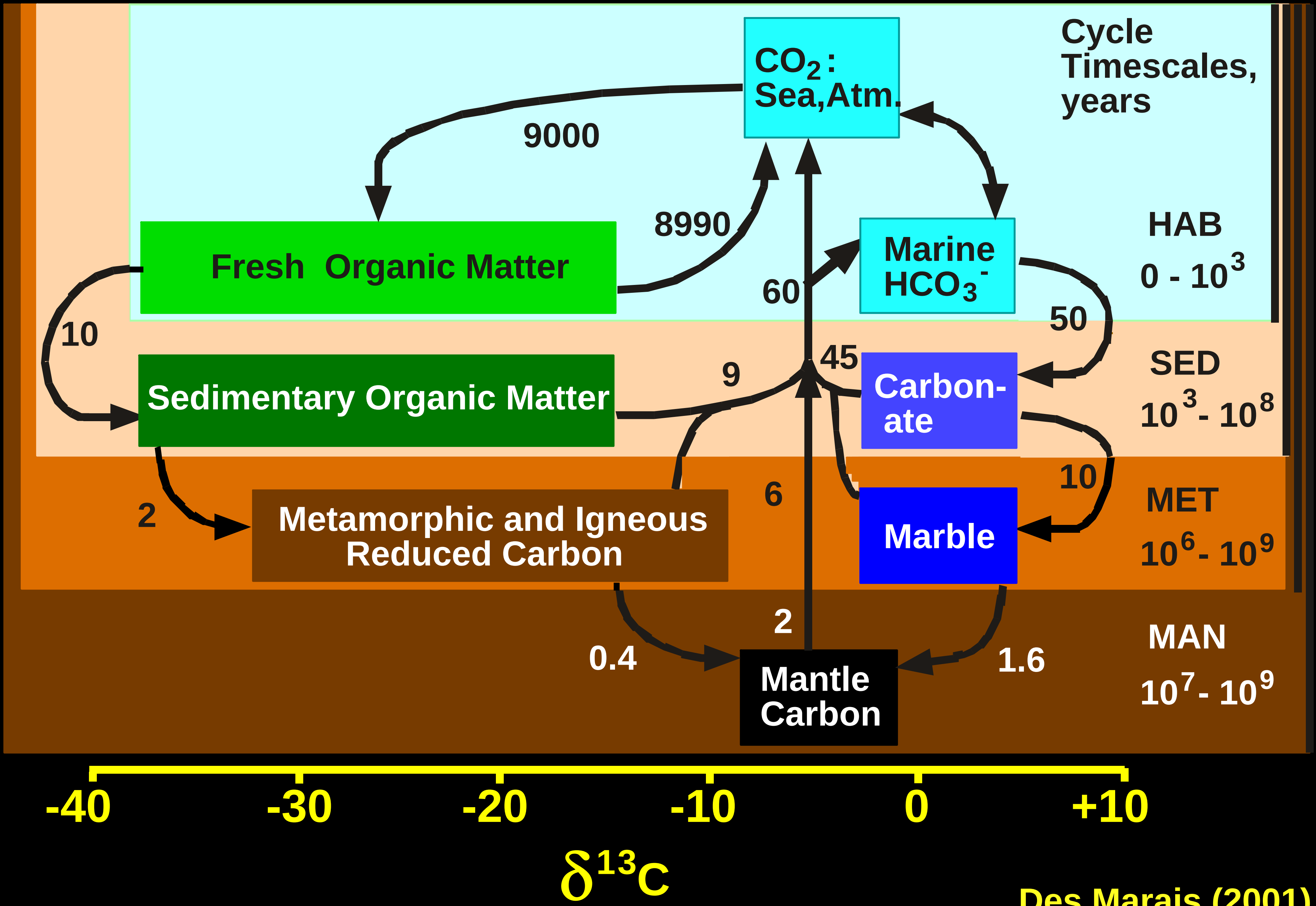
SED
$10^3 - 10^8$

MET
$10^6 - 10^9$

MAN
$10^7 - 10^9$

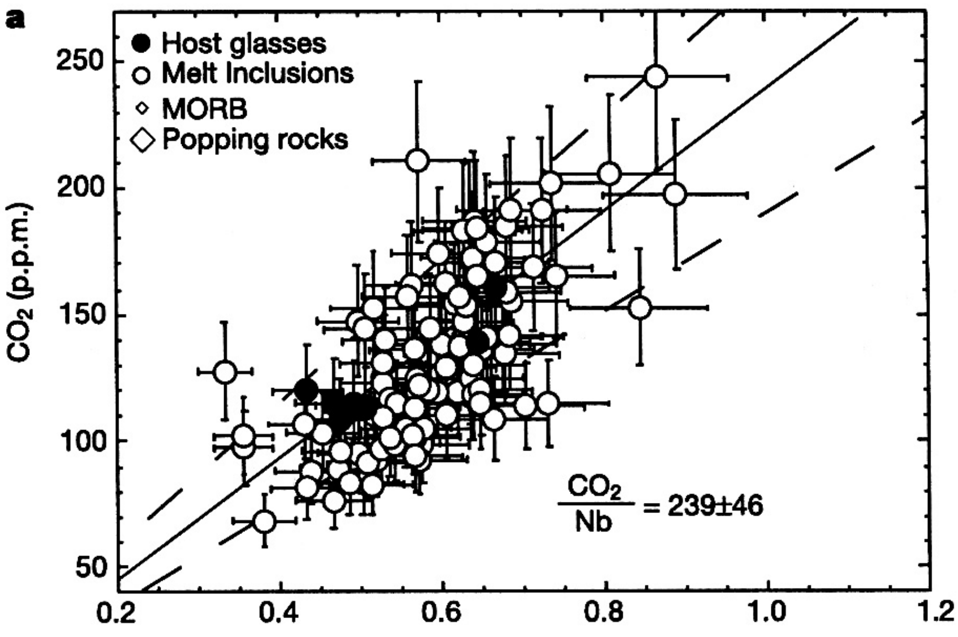
Biogeochemical Carbon Cycles

Present-Day Fluxes, x 10^{12} Moles per Year



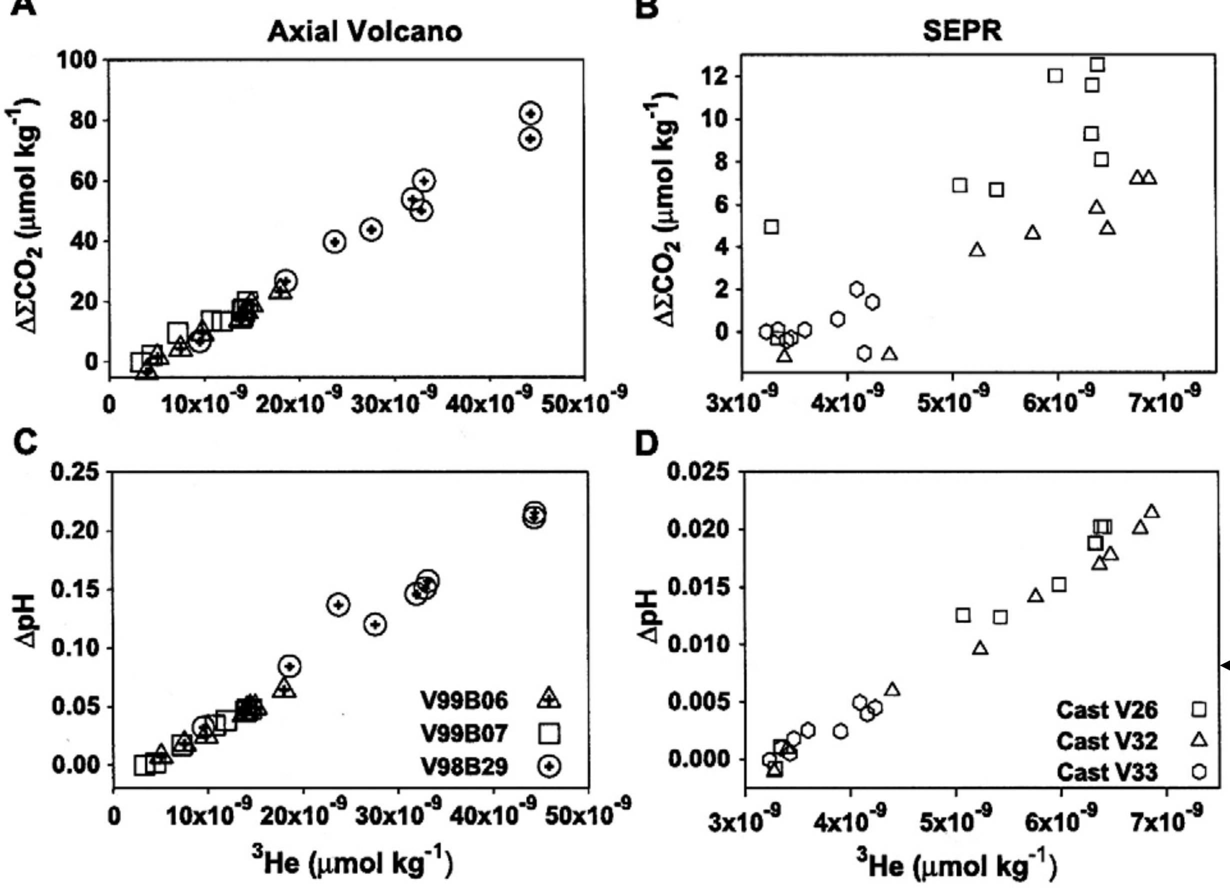
Des Marais (2001)

Estimating the flux of mantle carbon to the surface



C / Nb

Saal, et al., 2001



$\Delta\Sigma CO_2$ and decrease in pH (ΔpH) vs. ^3He at Axial Volcano (Panels A and C) and the SEPR 27.5–32.2°S (Panels B and D).

C / ^{3}He

Des Marais & Moore, 1984

← Resing et al., 2004

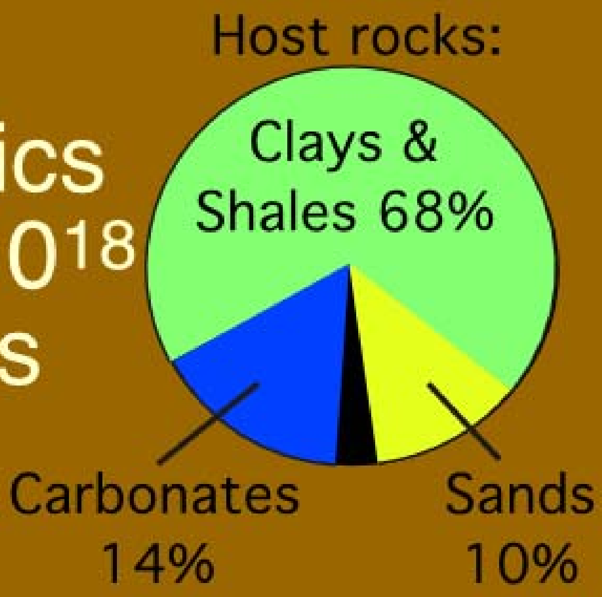
Earth's Carbon Budget

Biosphere, Oceans and Atmosphere ● 3.7 x 10^{18} moles

0.06 x 10^{18} moles

Crust

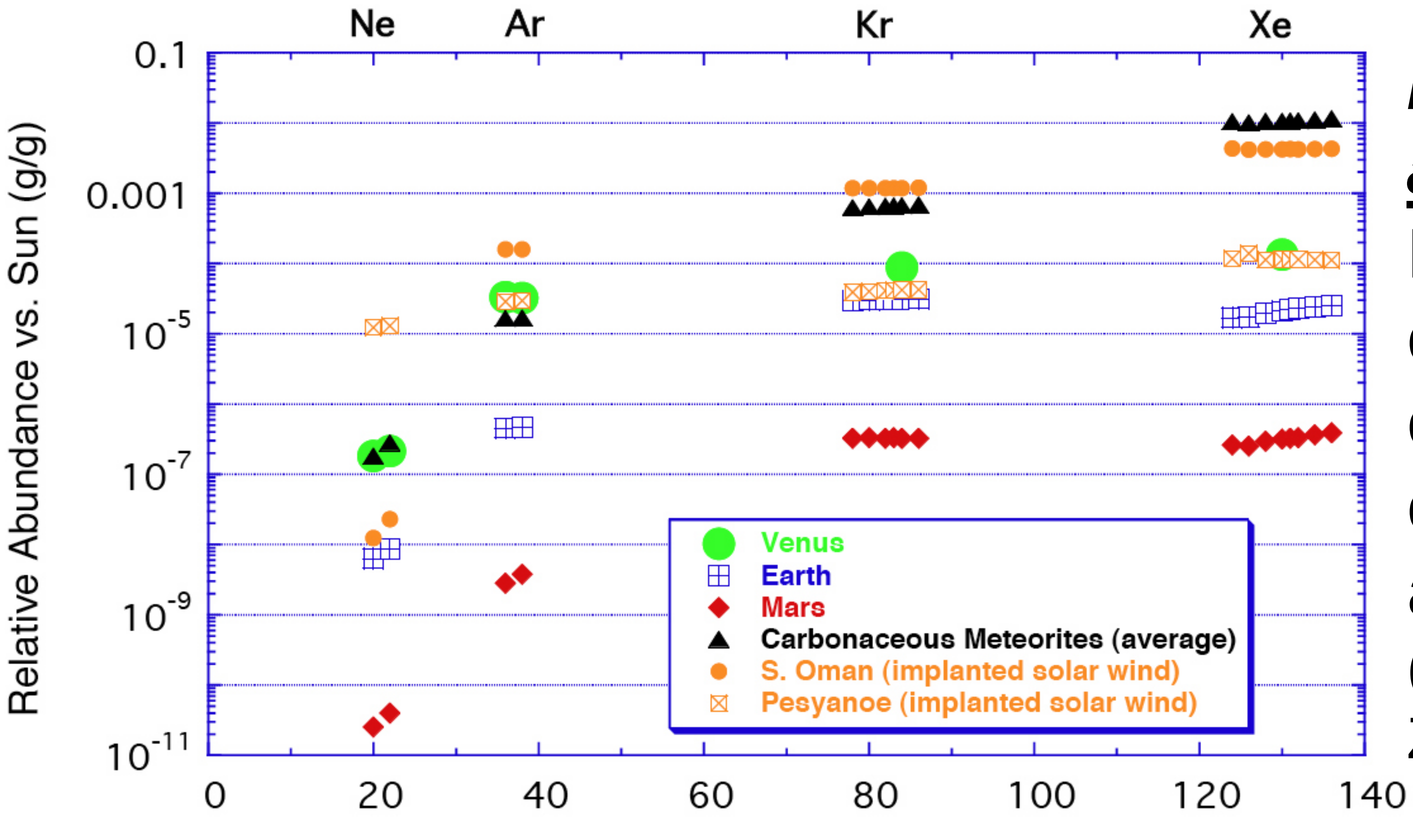
Organics 1200x10^{18} moles



Carbonates 6800 x 10^{18} moles

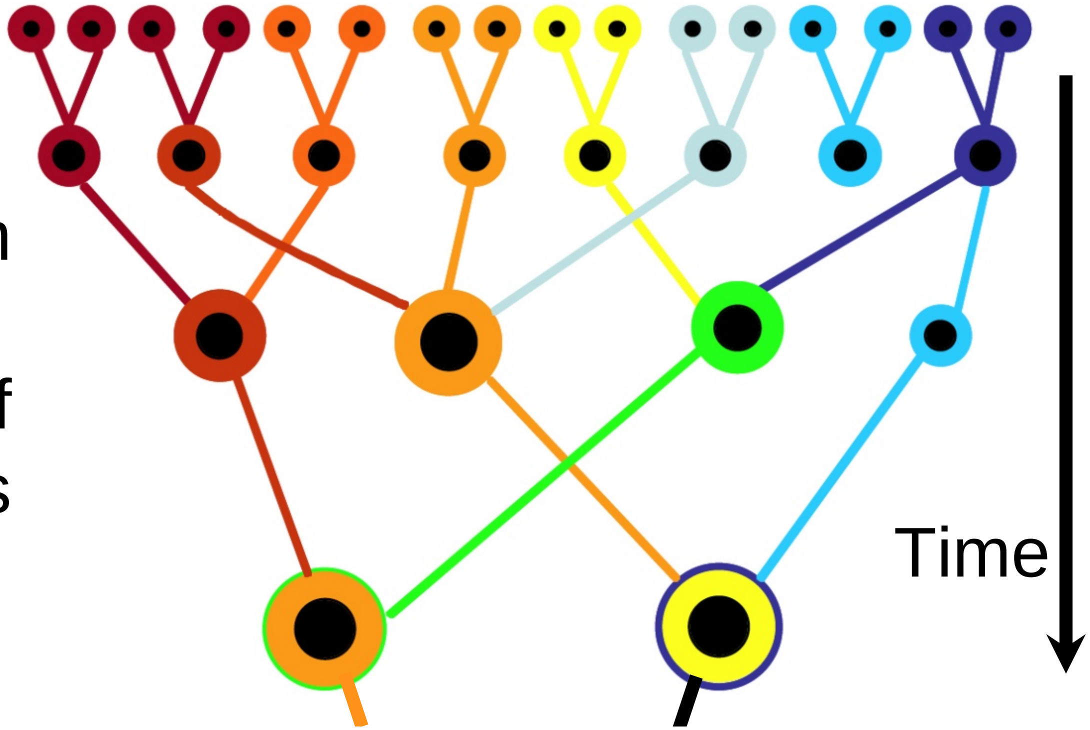
Mantle

~20,000 x 10^{18} moles



Rare gas & nitrogen abundance patterns

Earth & Mars match carbonaceous chondrites more closely than solar abundances
(Pepin, 1991;
Zahnle et al., 2007)

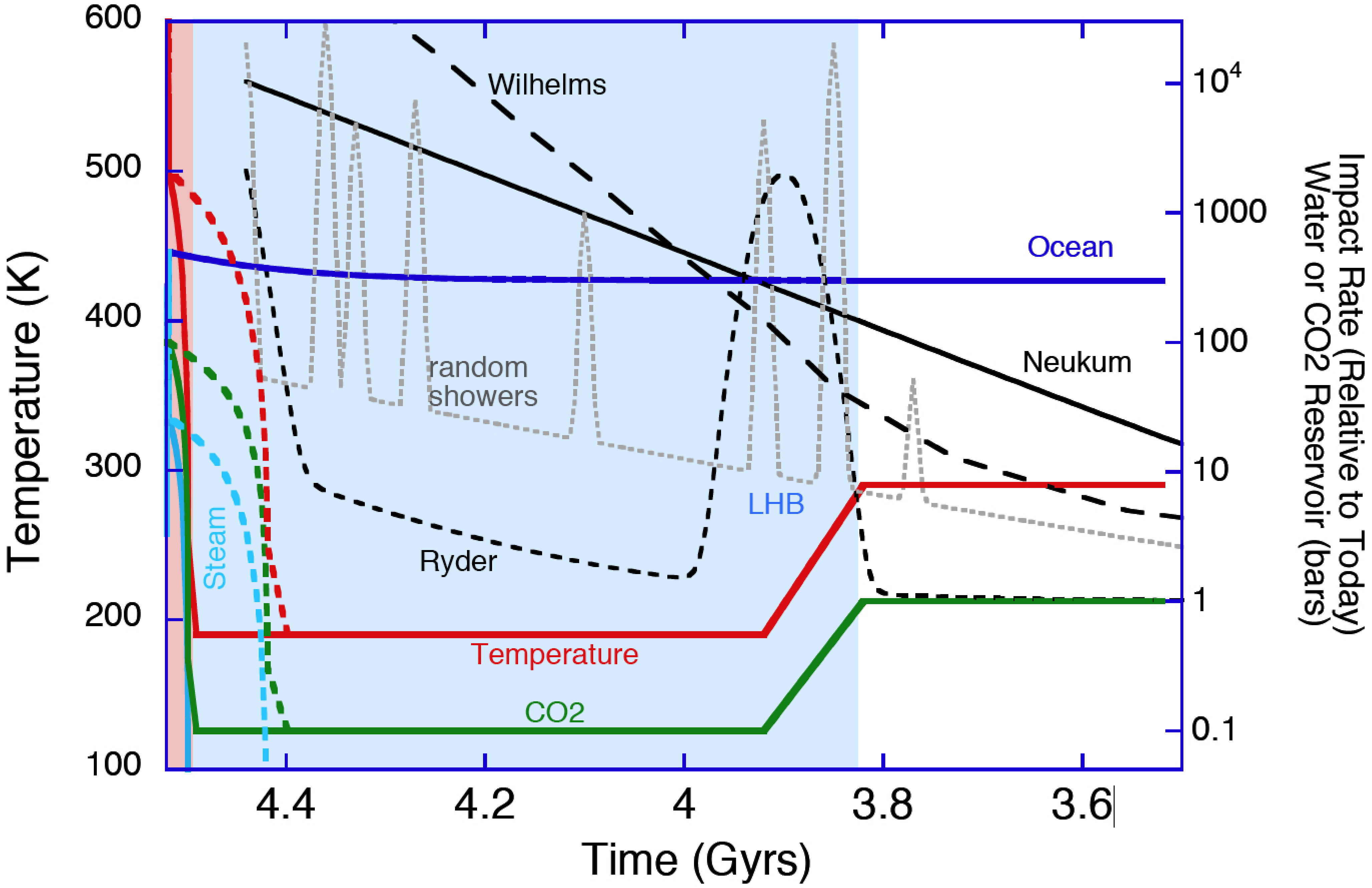


Earth accreted from coalescing planetesimals that had a broad range of abundances of volatiles

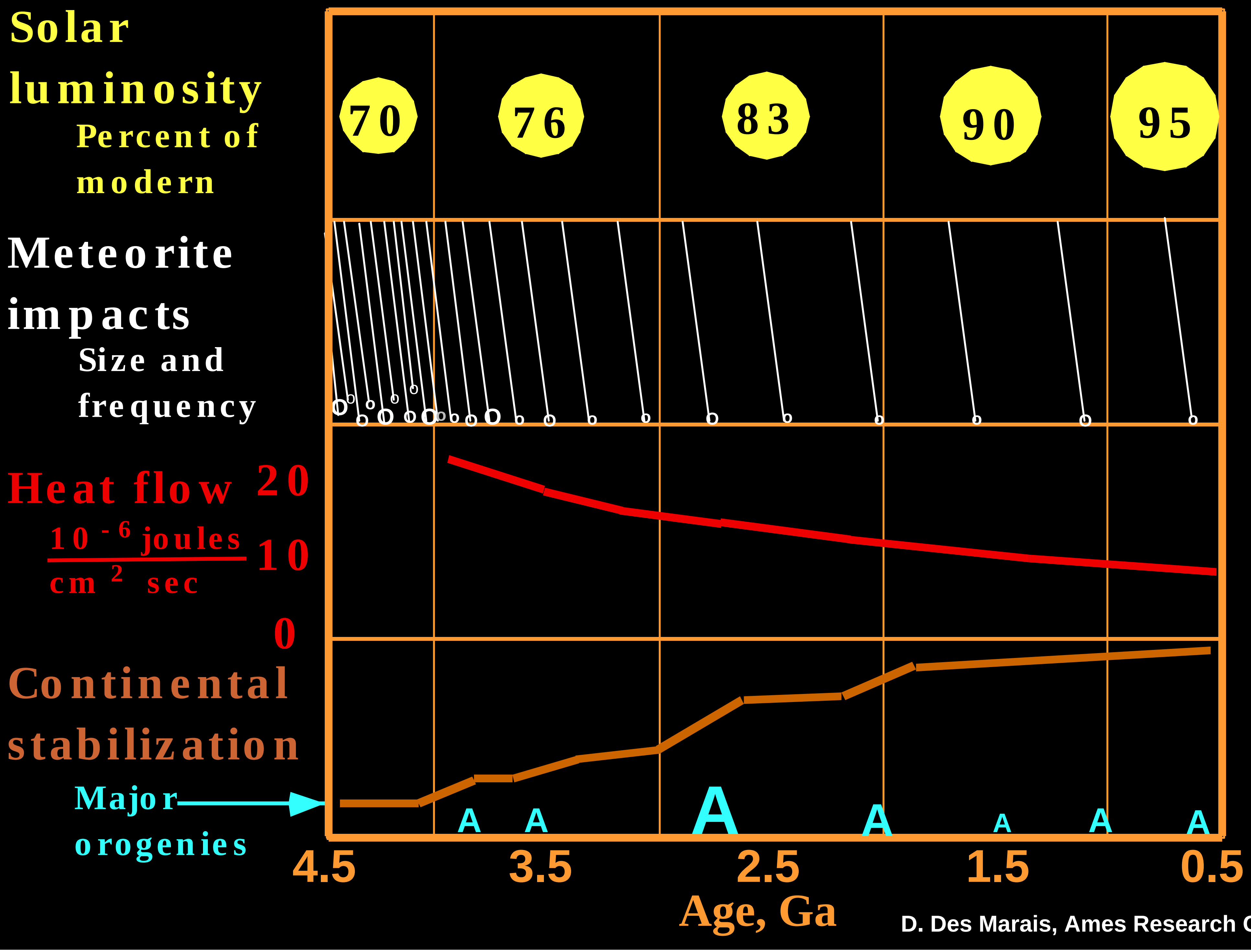
(Zahnle et al., 2007)

Hadean Impacts, Volatiles and Temperature

Zahnle et al., 2007



Evolution of Earth's Early Environment



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C subduction, Recent vs Archean (Des Marais, 1984)

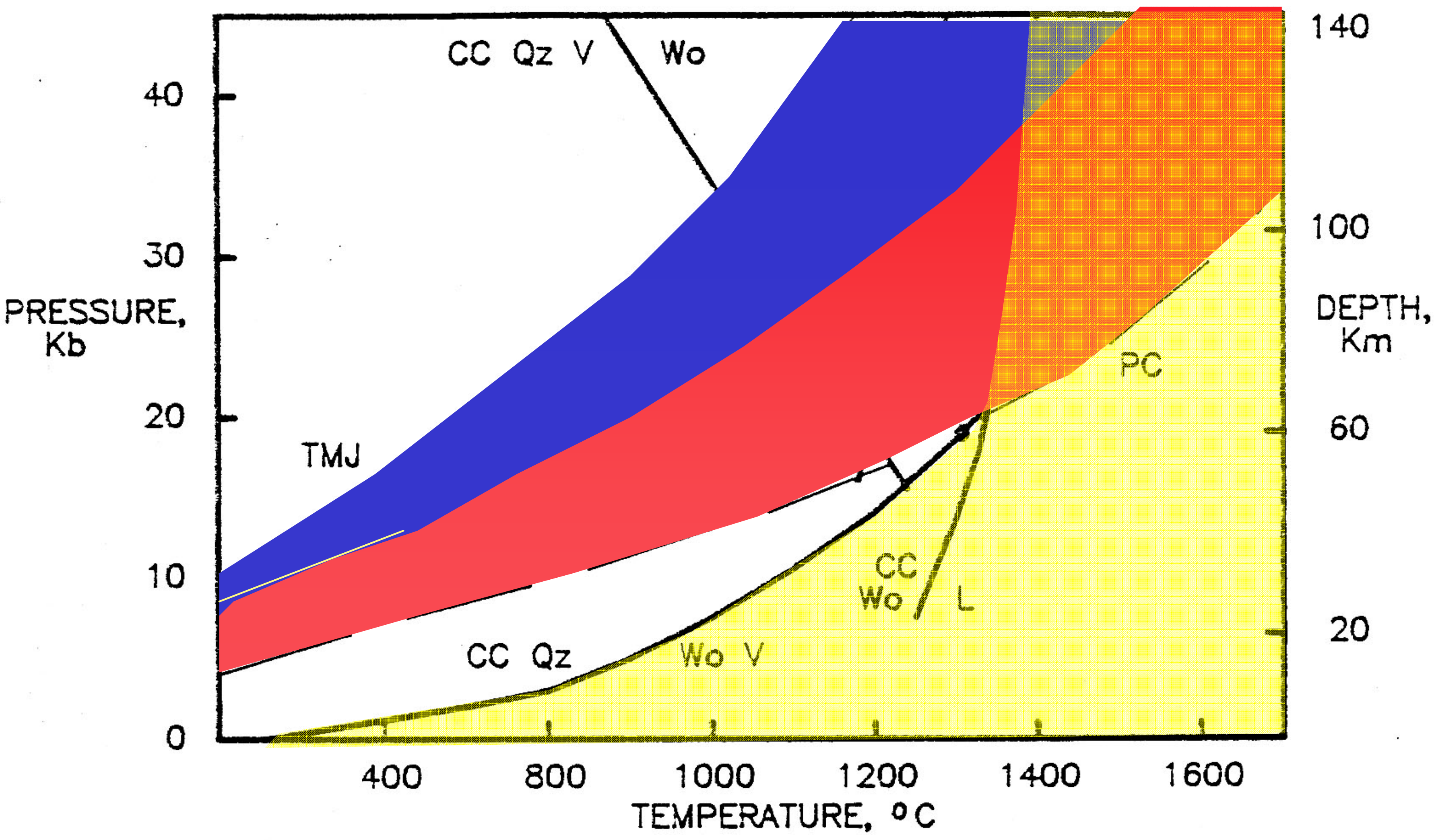
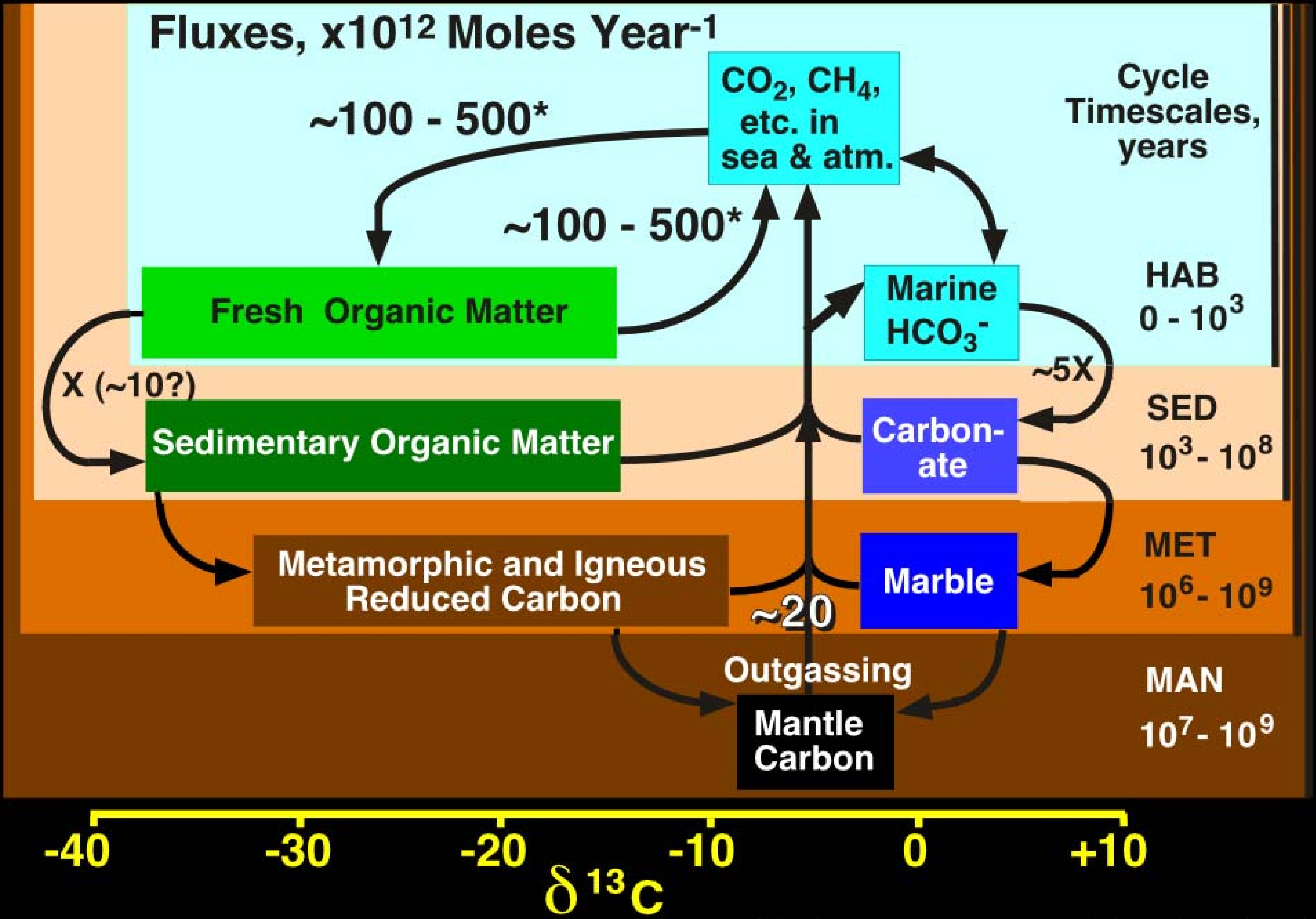


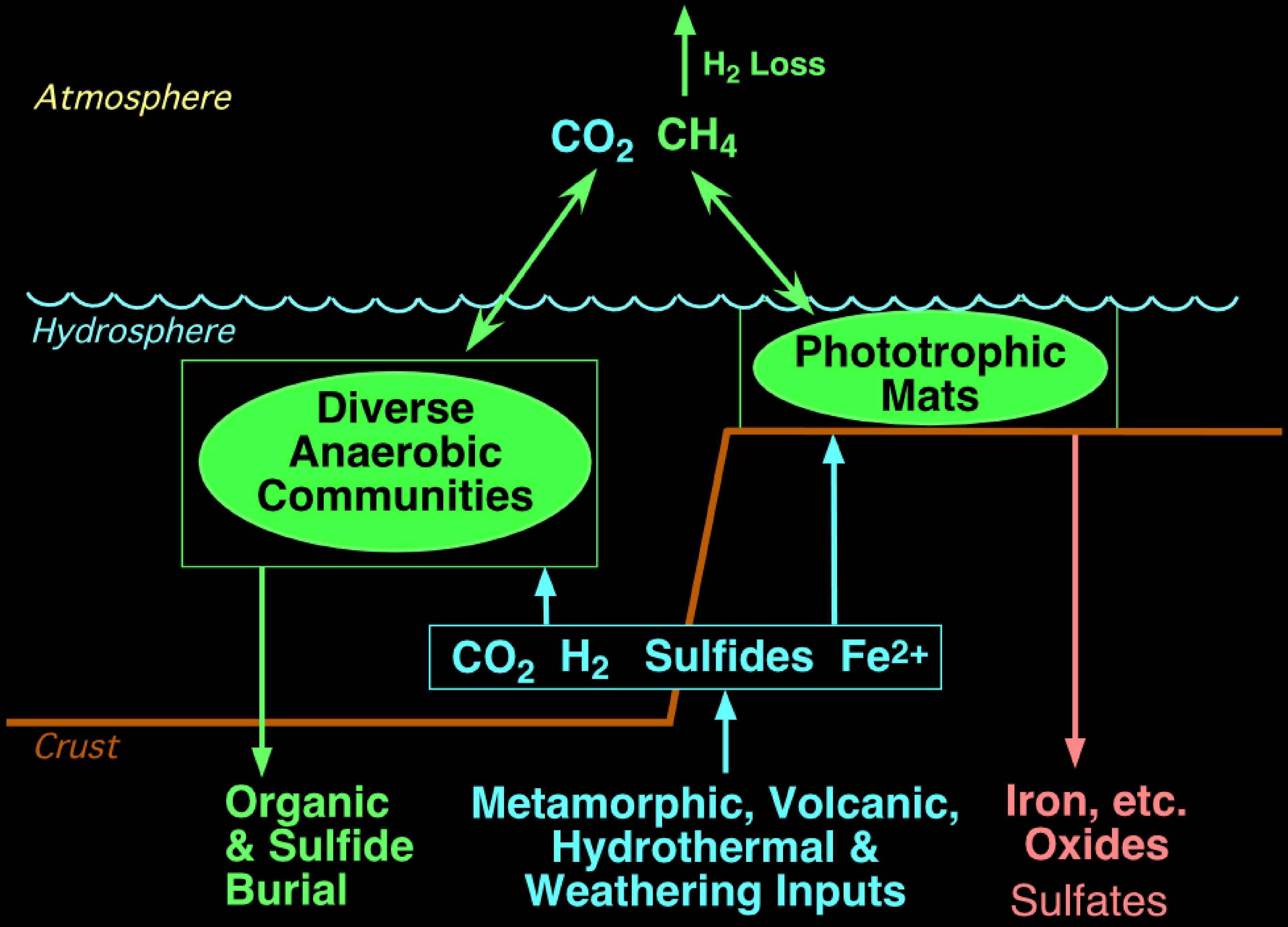
Fig. 1. Selected reactions involving calcite-quartz assemblages situated on the upper surface of a subducted slab, modified from Figures 8 and 9 of Huang et al. [1980]. Heavy lines delineate transformations between the following: CC - calcite, CO_2, L - liquid, Qz - Quartz, V - Vapor, and Wo - wollastonite, $Ca(SiO_3)$. The two heavy curved lines correspond to anhydrous conditions; the two heavy straight lines correspond to reactions occurring in the presence of CO_2-H_2O mixtures. The straight line shown for CC+Qz+V = Wo assumes P_{CO2} = 15 kbar. The straight line for Wo+V = L assumes P_{H2O} = 15 kbar. The two solid light lines are estimates of the present-day temperature along the

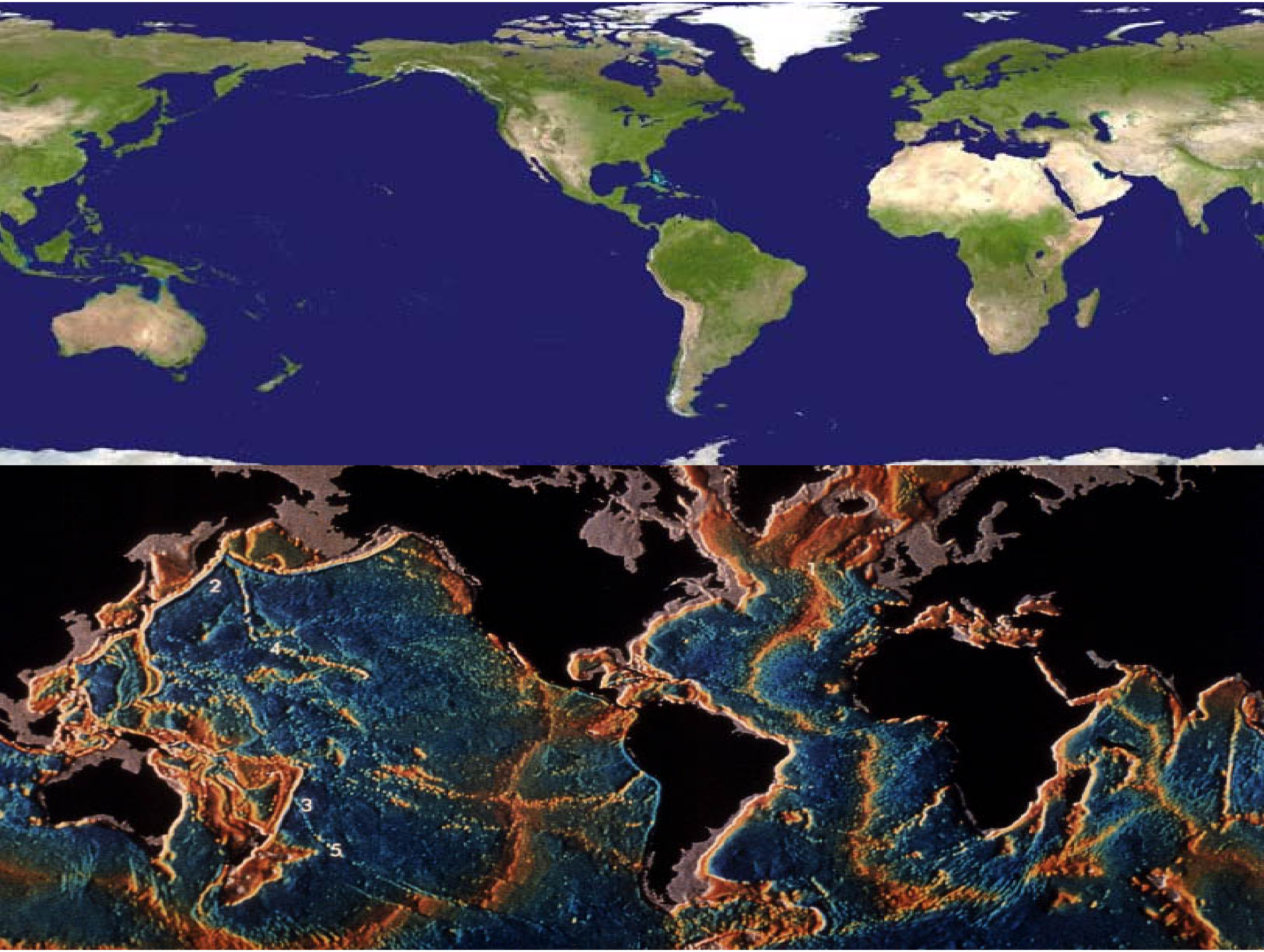
Biogeochemical C Cycles Before Oxygenic Photosynthesis?



*Canfield estimate: 170 - 500

Anoxygenic Photosynthesis in an Anoxic World

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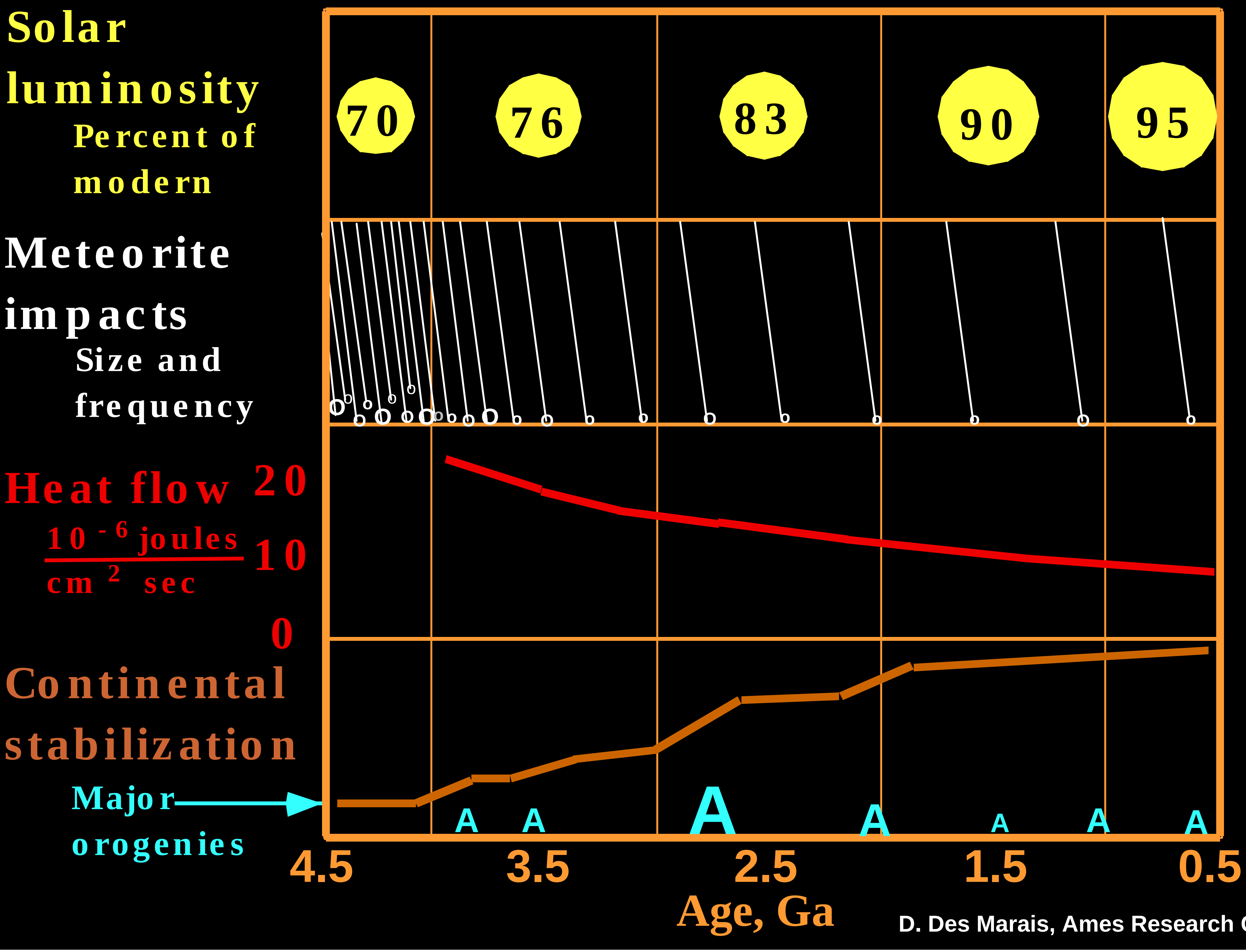
4
3
5

Evolution of Earth's Early Environment



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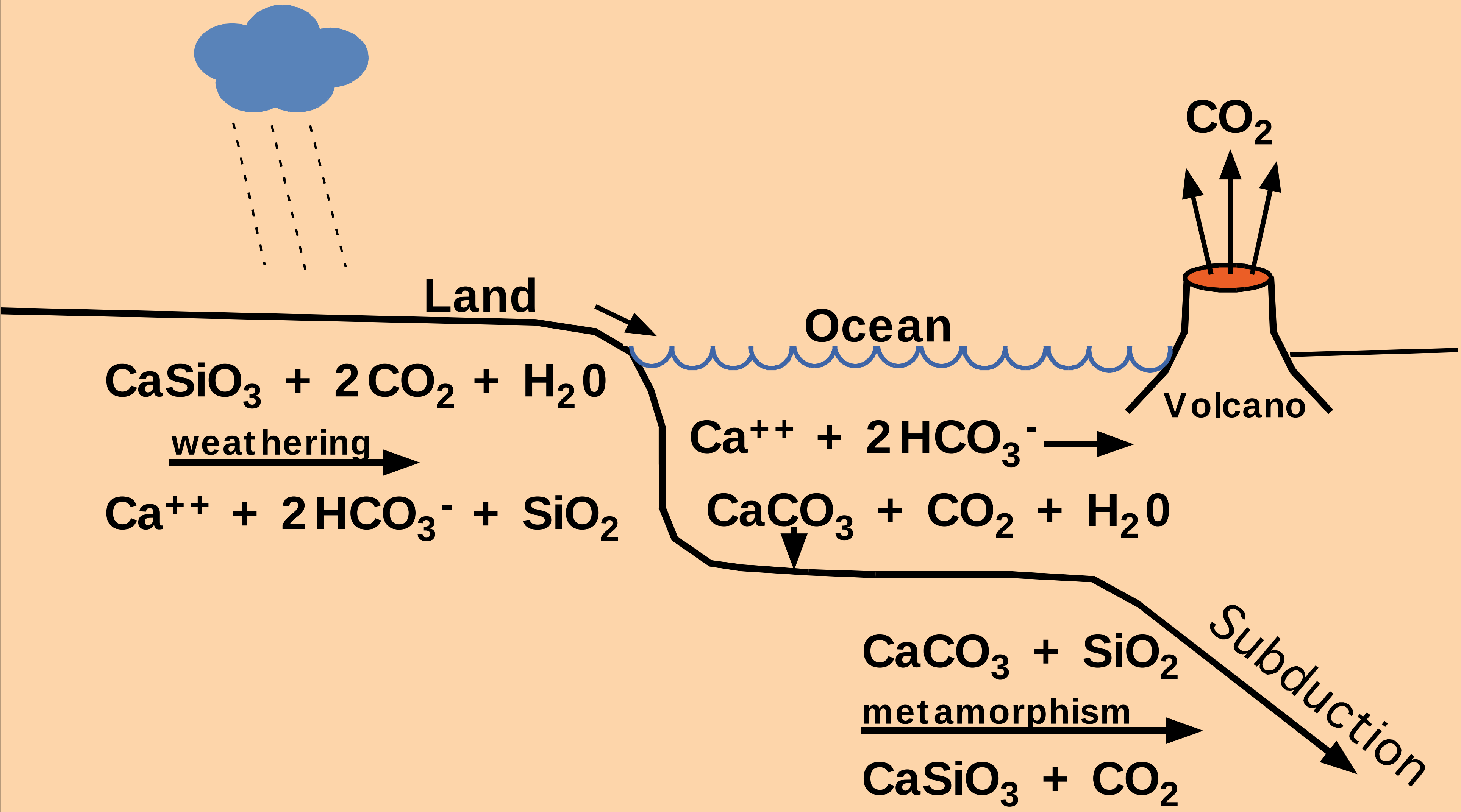
The Carbonate-Silicate Cycle



CO_2

Land

Ocean

Volcano

$$CaSiO_3 + 2CO_2 + H_20 \xrightarrow{\text{weathering}} Ca^{++} + 2HCO_3^- + SiO_2$$

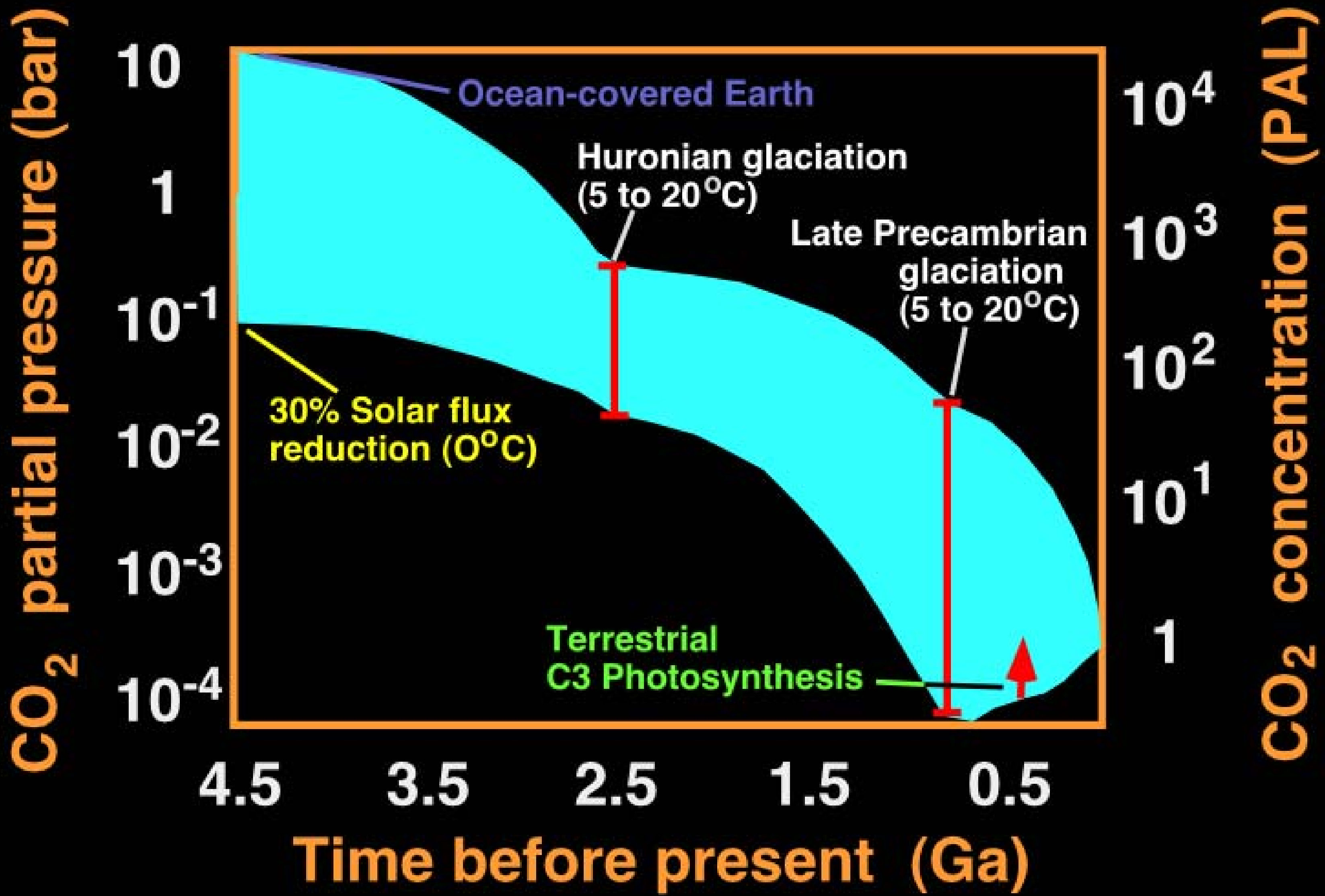
$$Ca^{++} + 2HCO_3^- \longrightarrow$$

$$CaCO_3 + CO_2 + H_20$$

Subduction

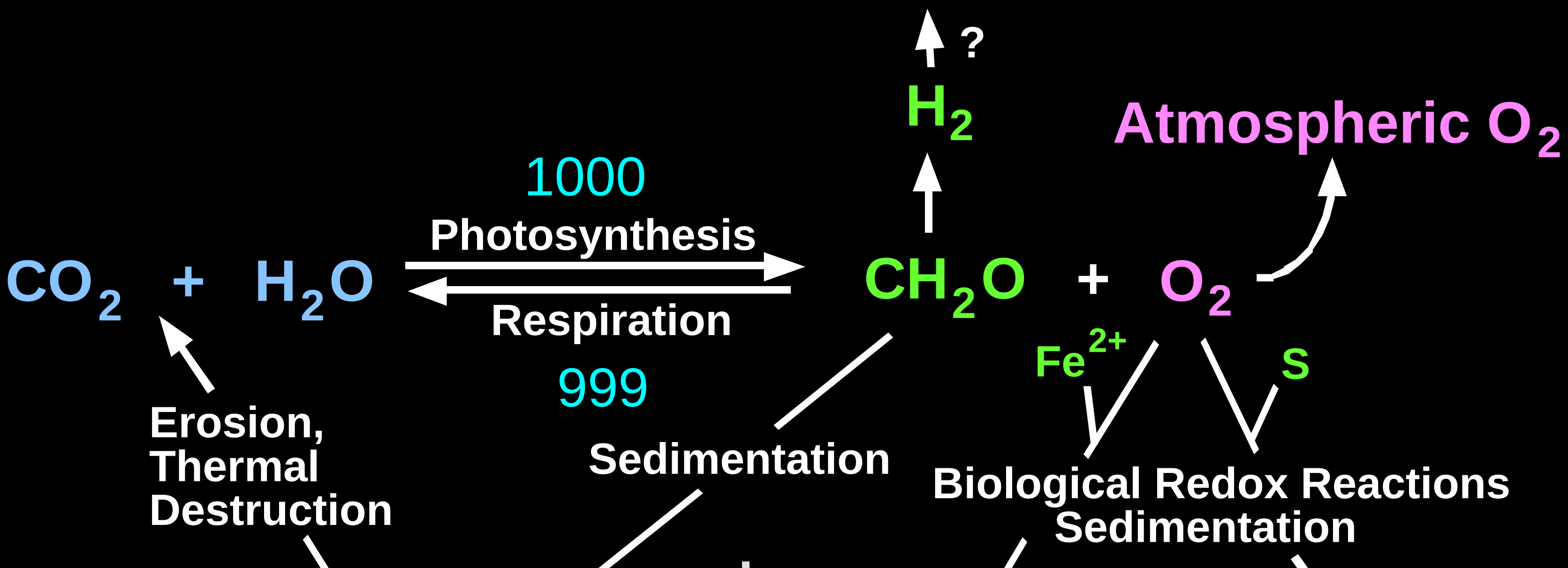
$$CaCO_3 + SiO_2 \xrightarrow{\text{metamorphism}} CaSiO_3 + CO_2$$

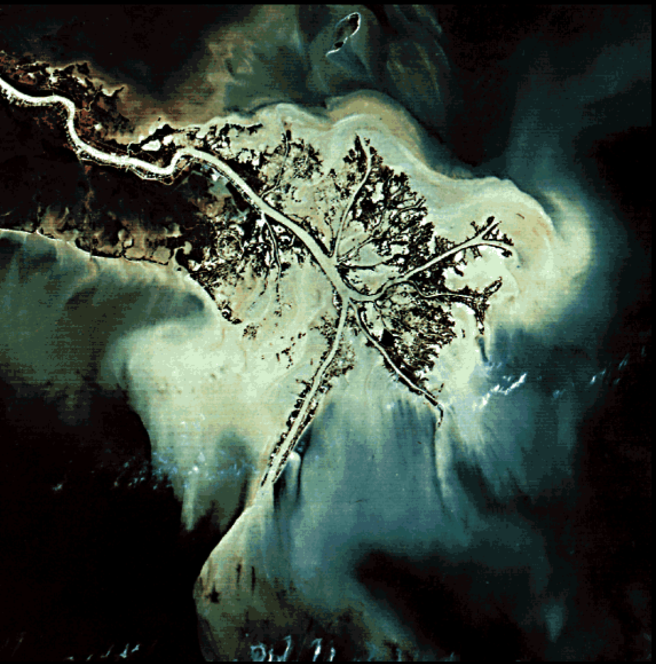
History of Earth's Atmospheric Carbon Dioxide Levels



Kasting

Productivity, Organic Burial, and Oxidant Reservoirs





Buried Organic Carbon

Plus Sulfide from Sulfate Reduction

Reduced

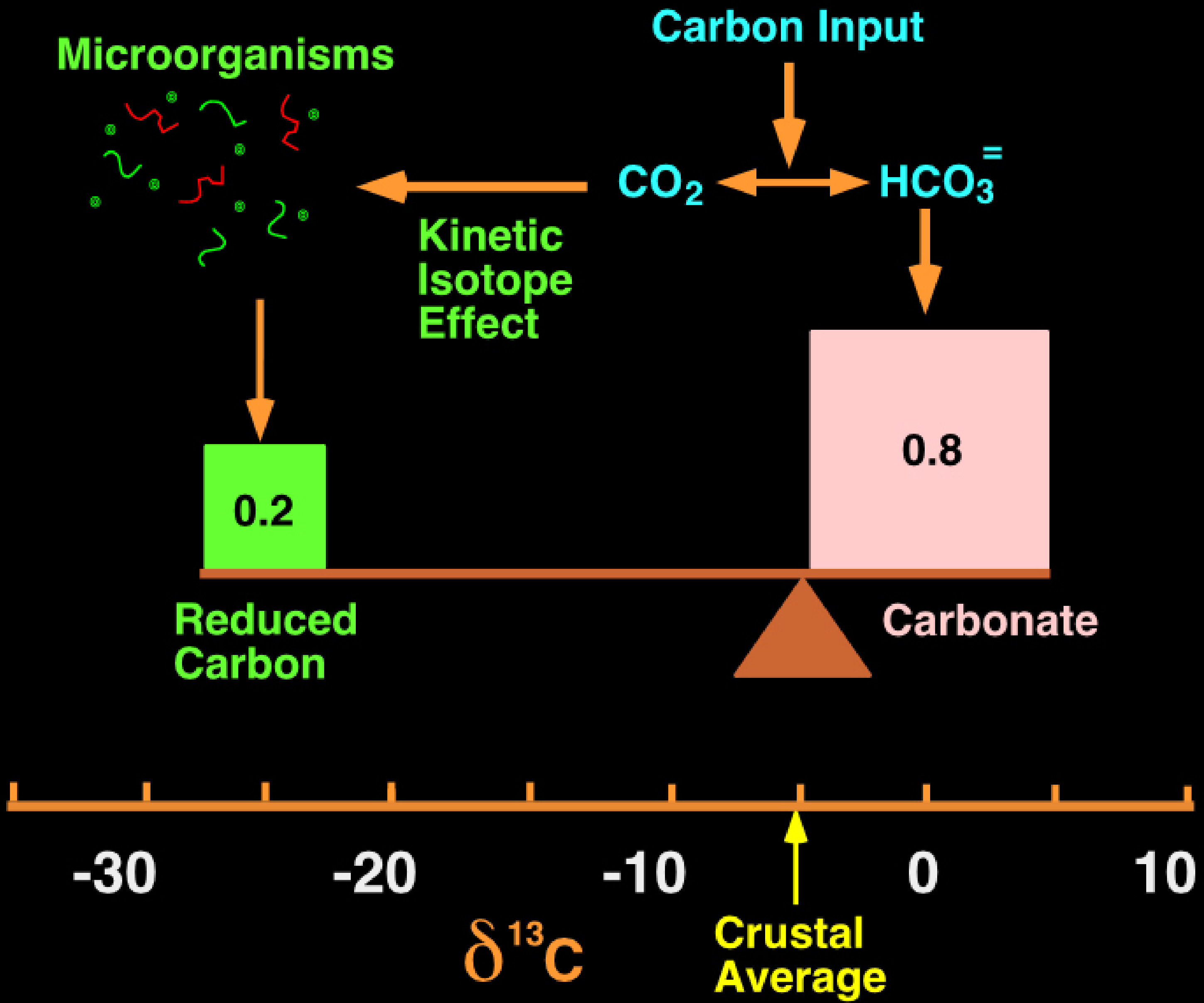
Buried Ferric Iron

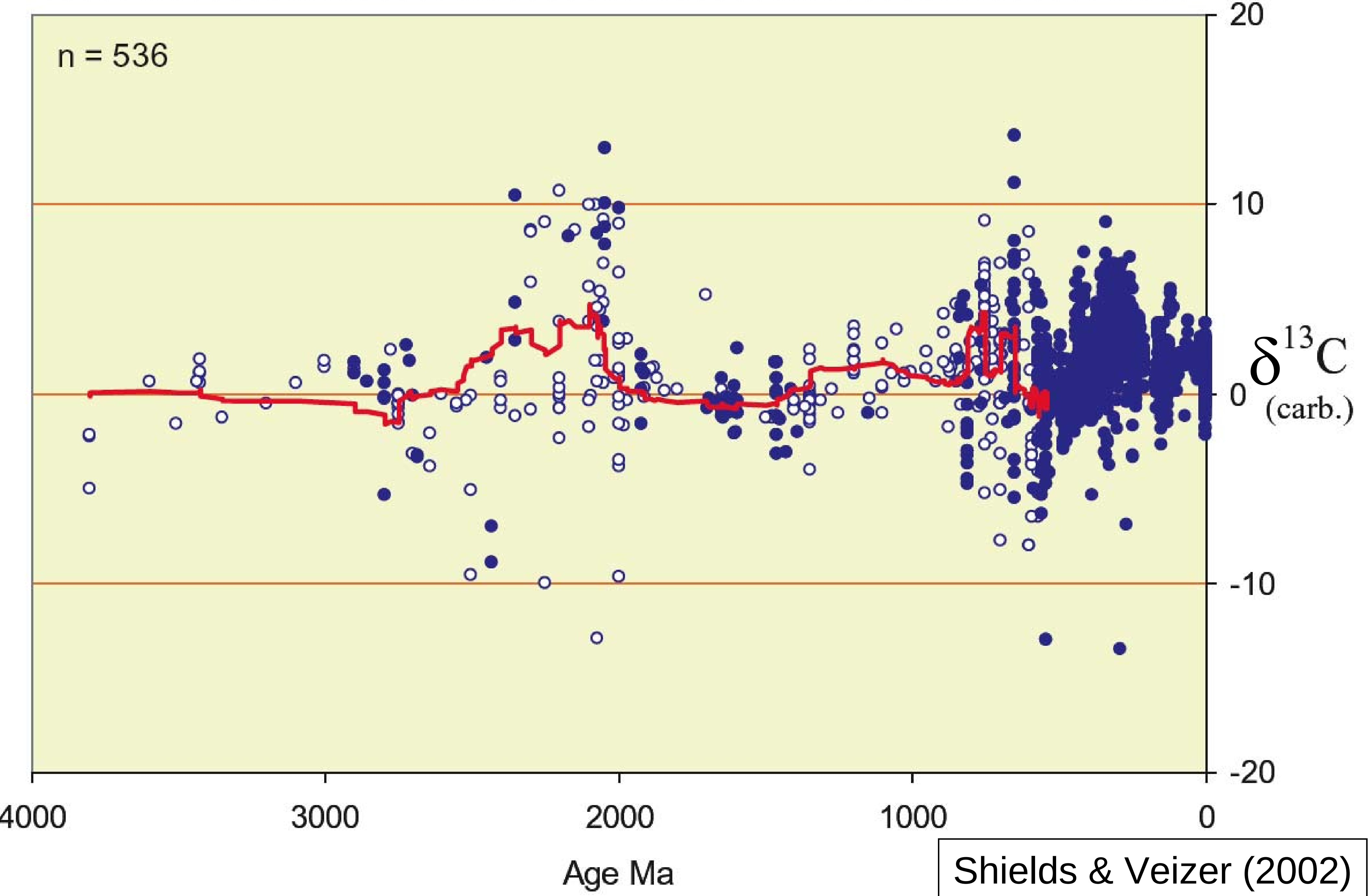
Sulfate in Seawater & Sediments

Oxidized

(Des Marais, 2002)

Isotopic Mass Balance of Crustal Carbon Reservoirs

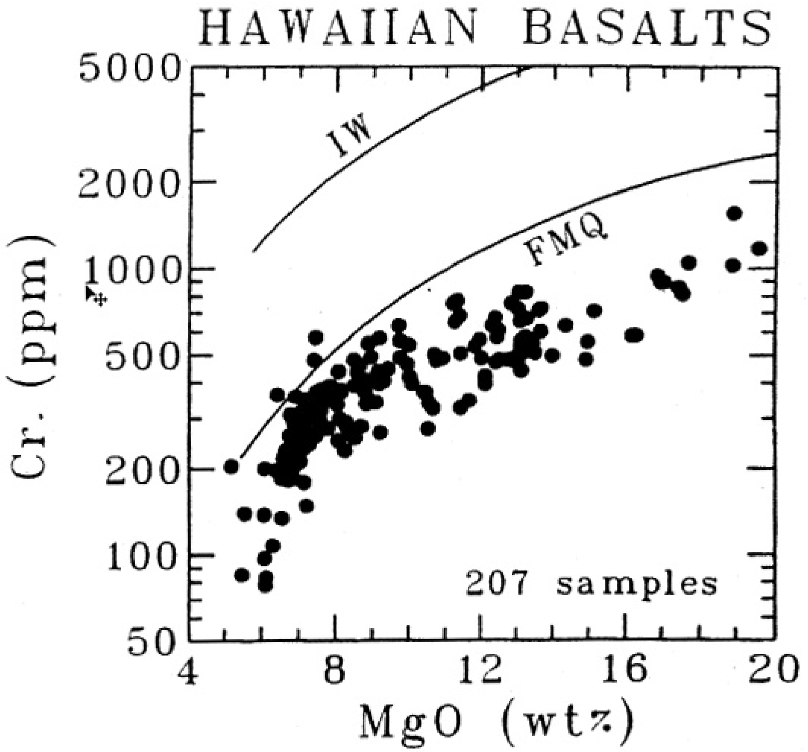


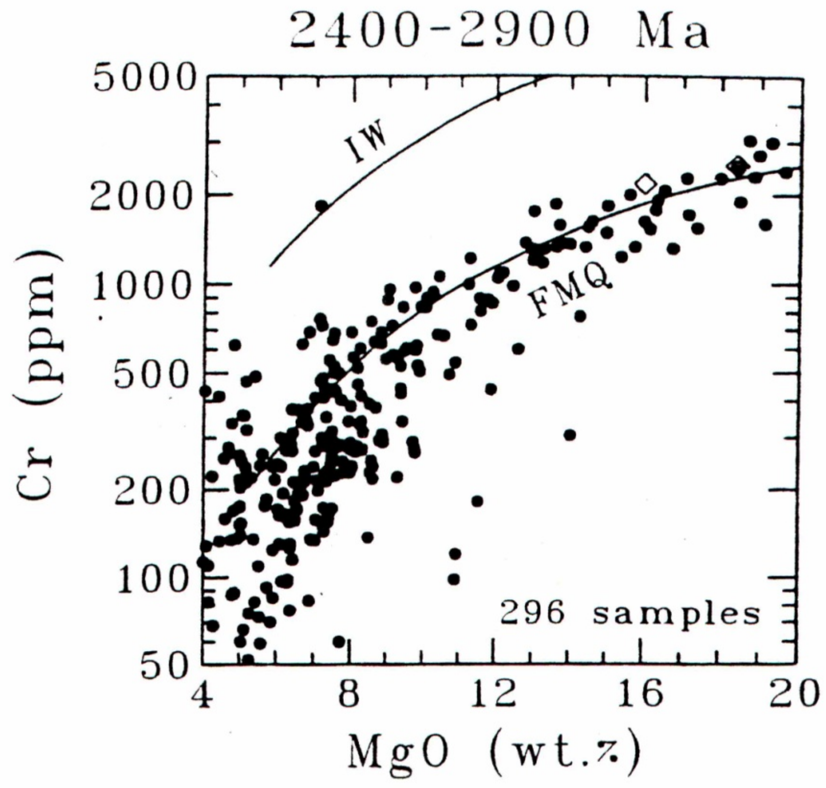


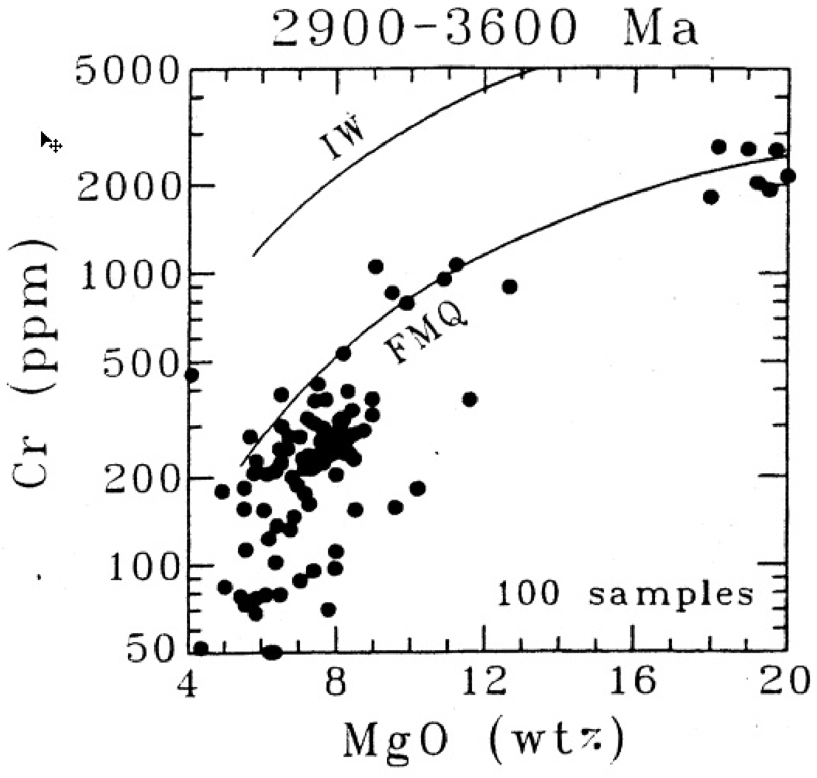
Shields & Veizer (2002)

Redox History of the Upper Mantle

Delano (2001)


HAWAIIAN BASALTS


2400-2900 Ma


2900-3600 Ma

The C Cycle during the Archean and Proterozoic

- Mantle-crust exchange dominated the Archean C cycles
  - Substantial C fluxes and crustal reservoirs
  - Redox control
  - Global biological productivity
  - Hydrogen escape to space
- Proterozoic trends altered the C cycles
  - Declining geothermal fluxes
  - Increasing solar luminosity
  - Oxygenic photosynthesis
  - H escape to space
  - Continents and tectonics

End

Carbon Isotopic Record in Sedimentary Carbonates and Organic Matter