GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet habitable?

Lecture 1

Tuesday 2 April 2019

Today:

- Logistics (course handout, introductions,
  <u>*no lecture this Thursday*</u>, designate presenters
  for Tue 10 paper presentation)
- Course outline, motivation, scope
- Earth history, post-Hadean

Course outline

Foundations (1-2 weeks)

- Earth history
- HZ concept, atmospheric science essentials
- Post-Hadean Earth system

Principles – how are habitable planets initiated and sustained? (4-5 weeks)

- Volatile supply, volatile escape
- Long-term climate evolution
- Runaway greenhouse, moist greenhouse

Specifics (~2 weeks)

- Early Mars
- Hyperthermals on Earth
- Oceans within ice-covered moons
- Exoplanetary systems e.g. TRAPPIST-1 system

PDFs of all required and suggested reading will be made available at http://geosci.uchicago.edu/~kite/geos32060_2019/

Particularly useful books:

Atmospheric evolution on inhabited and lifeless worlds, Catling & Kasting
e.g. http://geosci.uchicago.edu/~kite/doc/Catling_and_Kasting_ch_5.pdf

How to build a habitable planet, Langmuir & Broecker

Ingersoll, Planetary Climates (Princeton Primers)

Accessible and solid introductions:

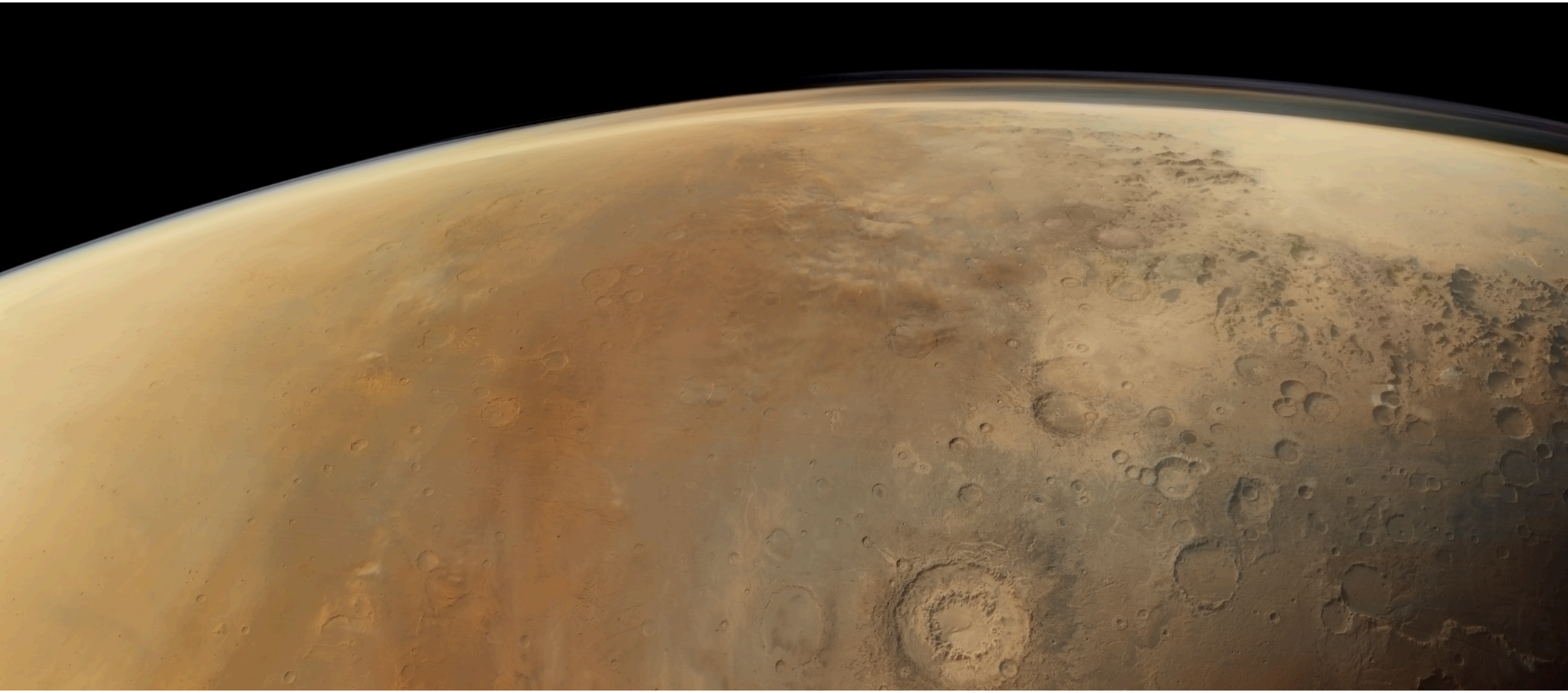
Life on a young planet, Andy Knoll (climate/life on Earth)

Planet Mars, Francois Forget (climate history on Mars)

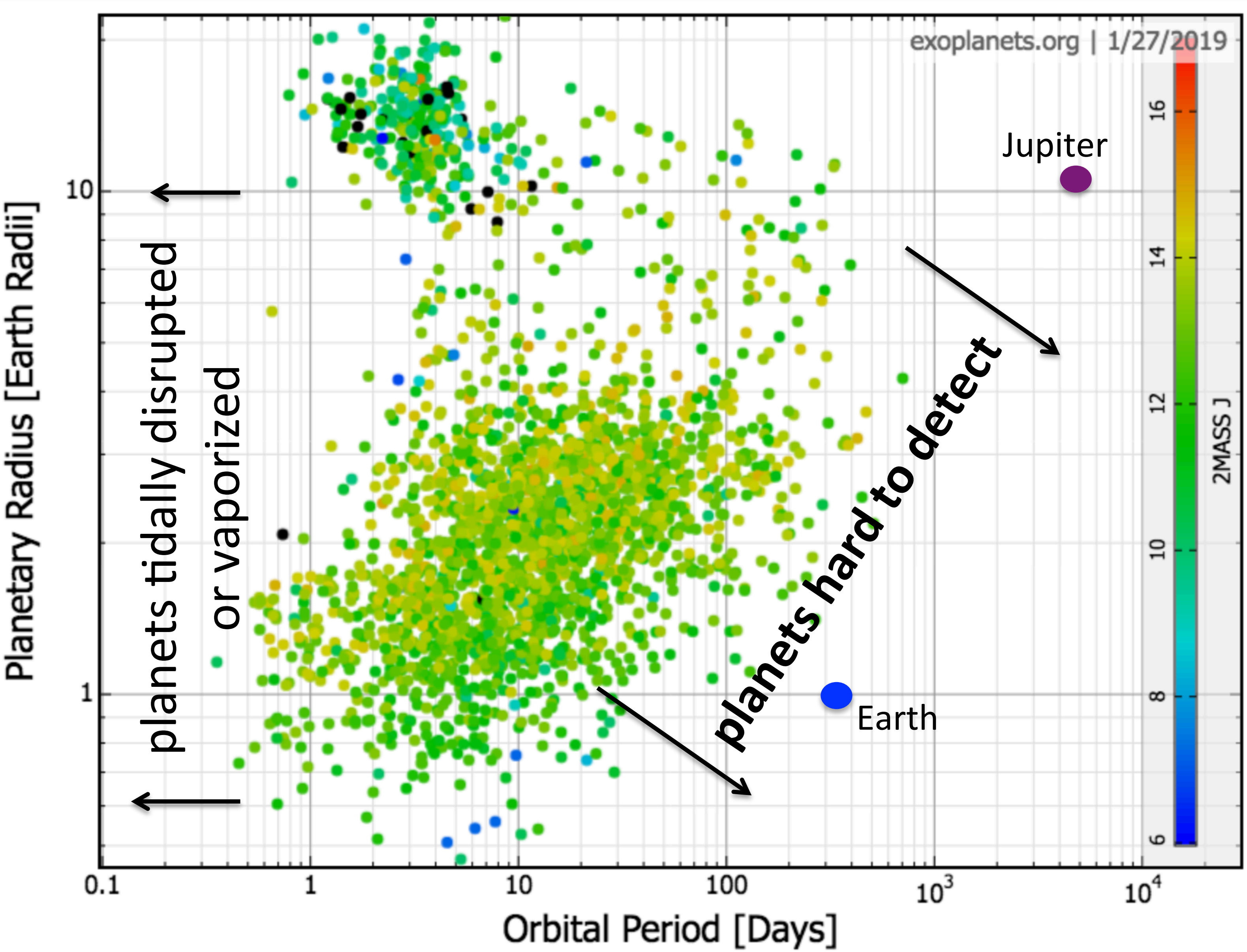
Five billion years of solitude, Lee Billings (exoplanets)

Lecture 1 Key points

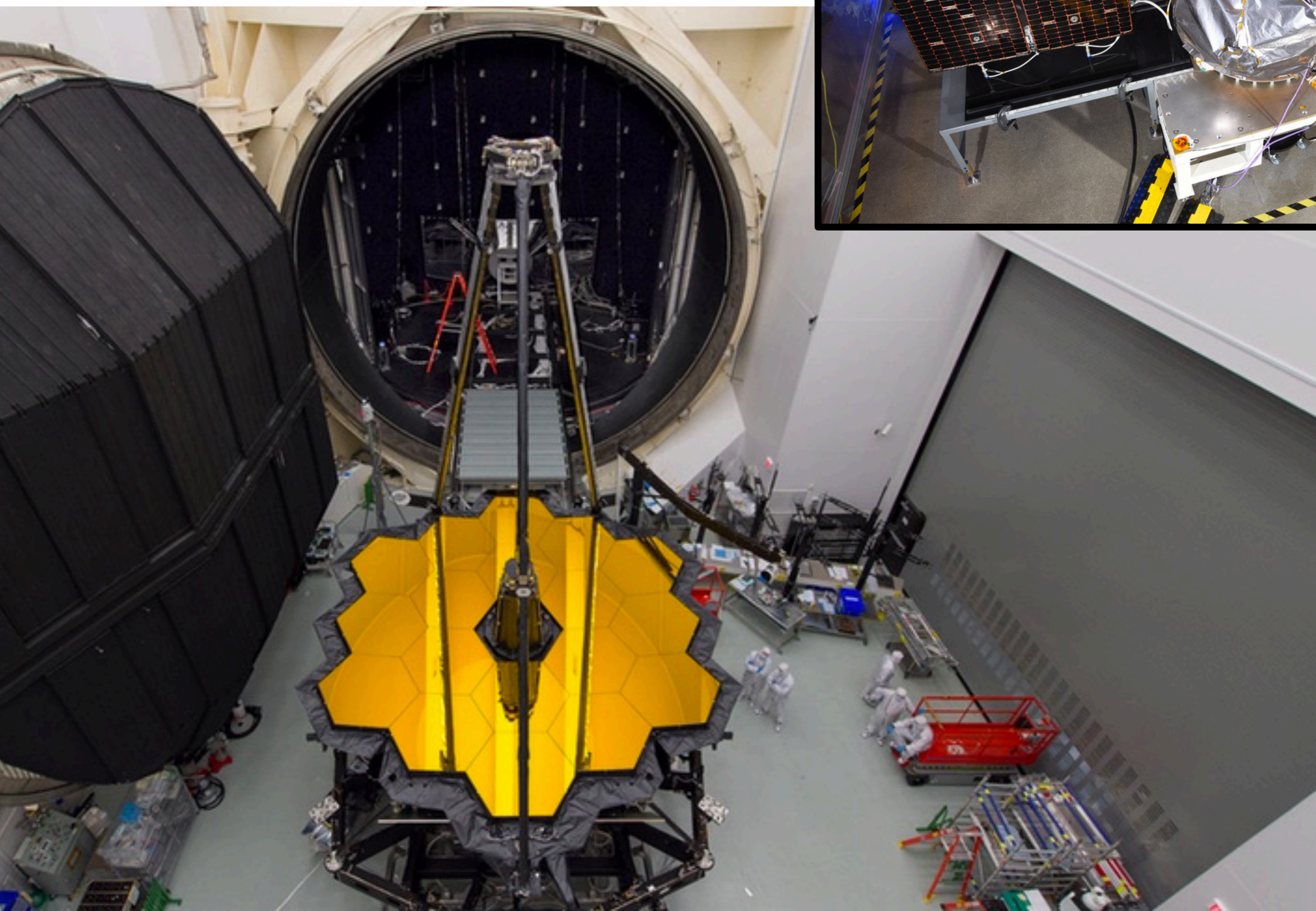
- **A useful definition of a habitable world is one that maintains T < 400 K liquid water on its surface continuously for timescales that are relevant for biological macroevolution**
- **Earth has stayed habitable for >3 Gyr**
  - Continuously
  - Earth inhabited only by microbes pre-1 Gya
- A \`difficult step' is a step in biological evolution whose characteristic wait time (given a habitable planet) is >> 10 Gyr. There are at least three candidate difficult steps on the evolutionary path leading to people.
- Earth's continuous habitability implies that Earth's climate has stayed within the habitable range at least for the last 3.5 Ga
  - **However, Earth's pO_2, pCO_2, and ocean chemistry have changed over time.**

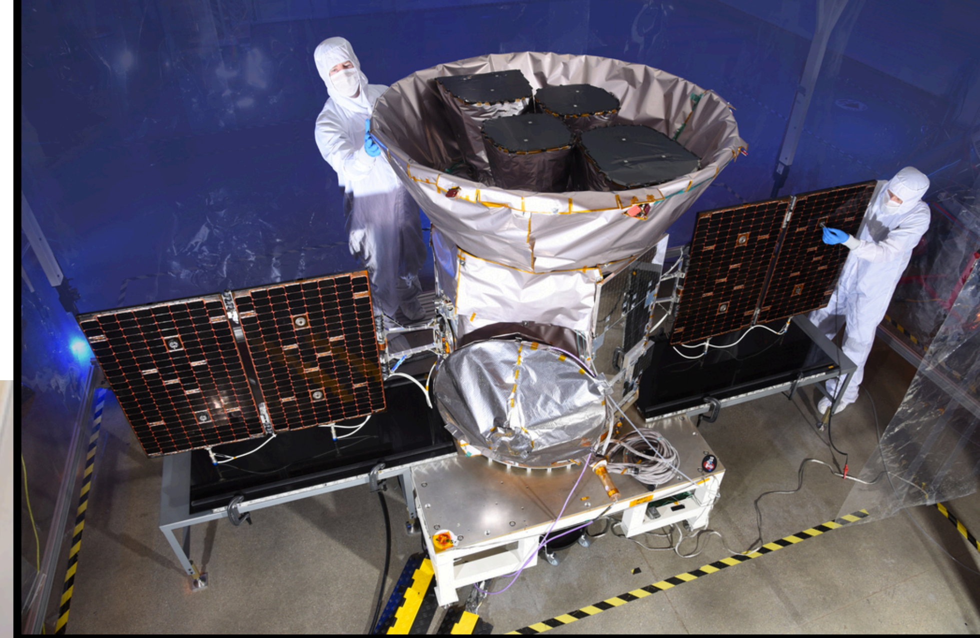


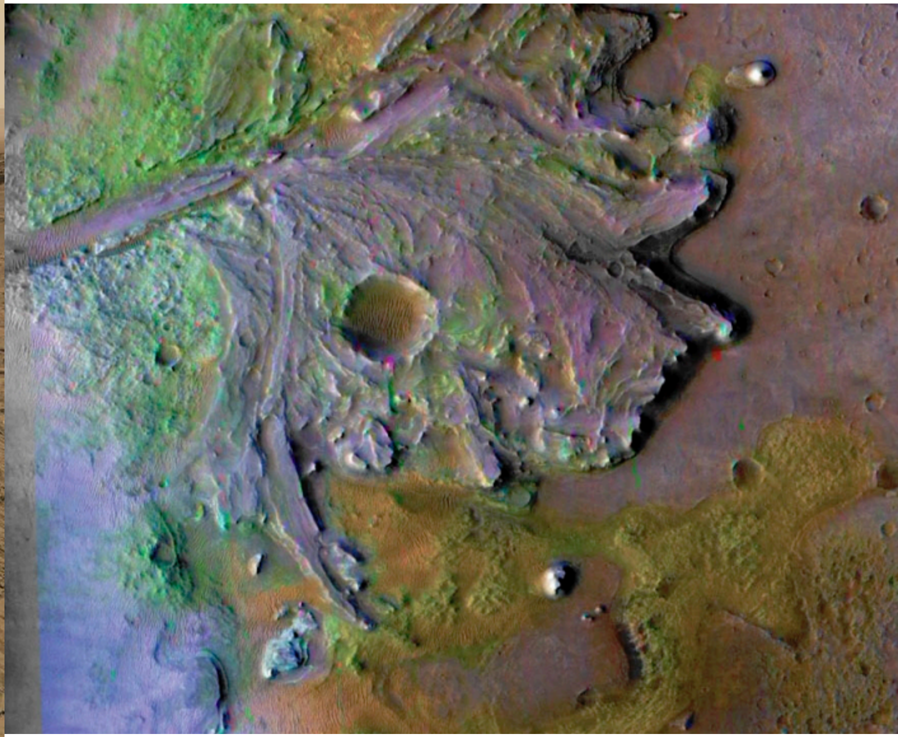
Planets are numerous … and many have atmospheres



For more information: Madhusudhan et al., "Exoplanetary atmospheres,"arXiv:1402.1169
Winn & Fabrycky, "Occurrence and architecture of exoplanetary systems," Annual Reviews, 2015



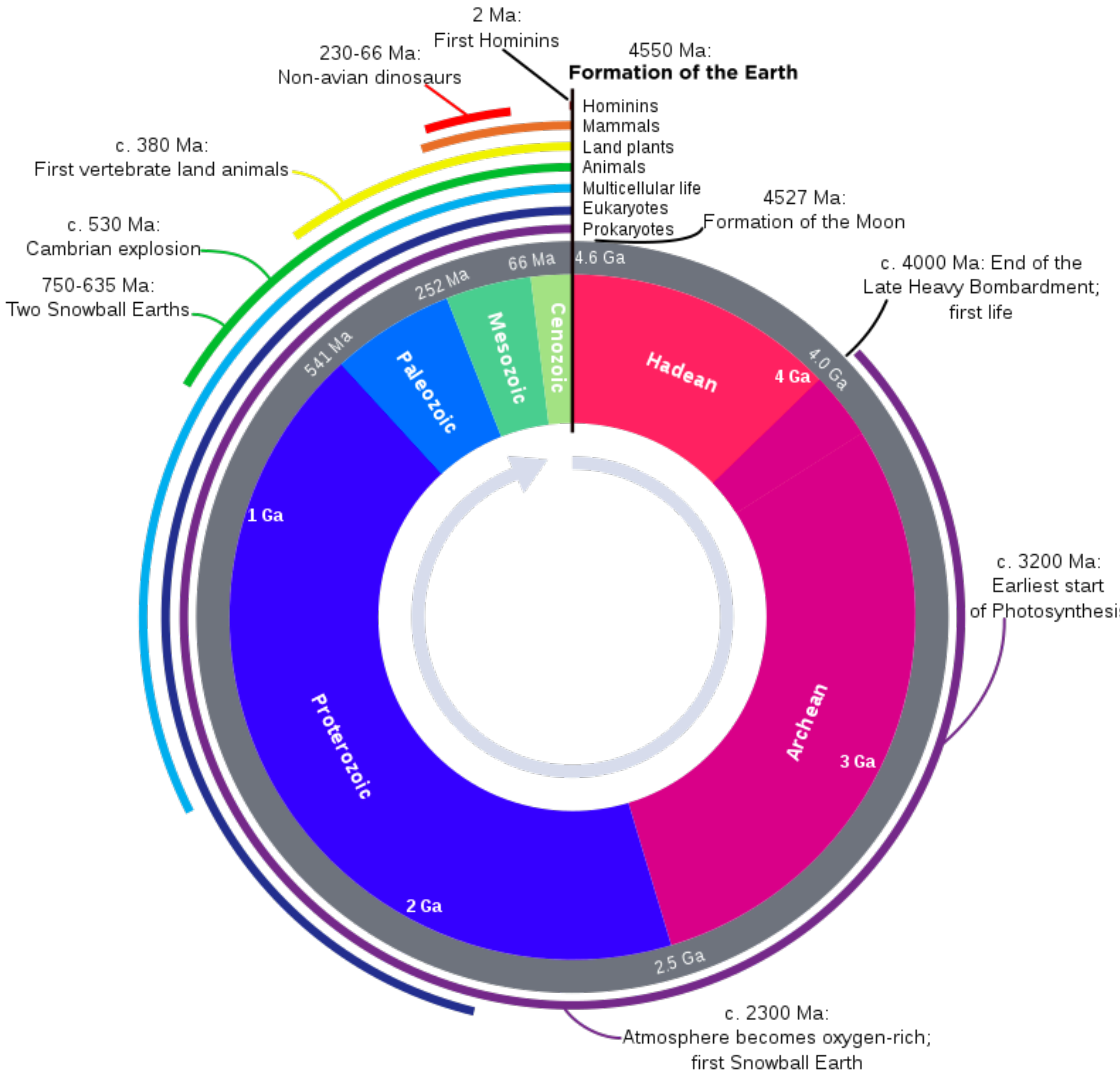




What makes a planet habitable?

For the purposes of this course:
A planet is a sub-stellar mass object that has never undergone nuclear fusion and which has sufficient self-gravitation to assume a spheroidal shape adequately described by a triaxial ellipsoid regardless of its orbital parameters.

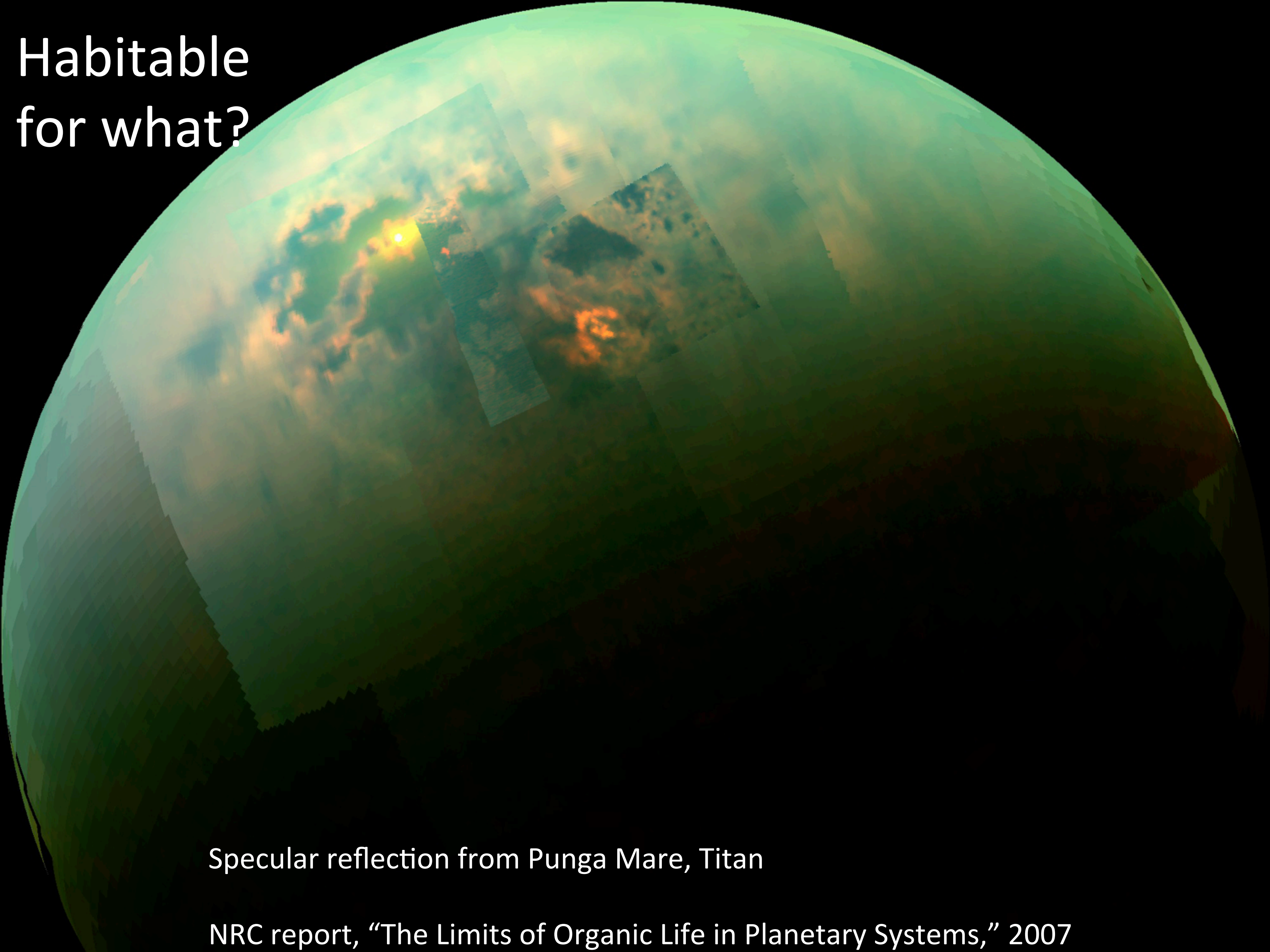
For the purposes of this course:
A habitable exoplanet maintains $T<400K$ liquid water on its surface continuously for timescale that are relevant for biological macroevolution ($>>10^7$ yr). Sub-ice oceans in extrasolar planetary systems may be habitable, but this cannot be confirmed from Earth by remote sensing. (Sub-ice oceans will be covered in Week 9).


2 Ma:
First Hominins
230-66 Ma:
Non-avian dinosaurs
4550 Ma:
Formation of the Earth
Hominins
Mammals
Land plants
Animals
Multicellular life
Eukaryotes
Prokaryotes
4527 Ma:
Formation of the Moon
c. 380 Ma:
First vertebrate land animals
c. 530 Ma:
Cambrian explosion
750-635 Ma:
Two Snowball Earths
c. 4000 Ma: End of the
Late Heavy Bombardment;
first life
4.6 Ga
66 Ma
252 Ma
541 Ma
Cenozoic
Mesozoic
Paleozoic
Hadean
4 Ga
4.0 Ga
1 Ga
Proterozoic
Archean
3 Ga
2 Ga
2.5 Ga
c. 3200 Ma:
Earliest start
of Photosynthesis
c. 2300 Ma:
Atmosphere becomes oxygen-rich;
first Snowball Earth

Habitable for what?

Carl Sagan's "Cosmos"

Habitable for what?

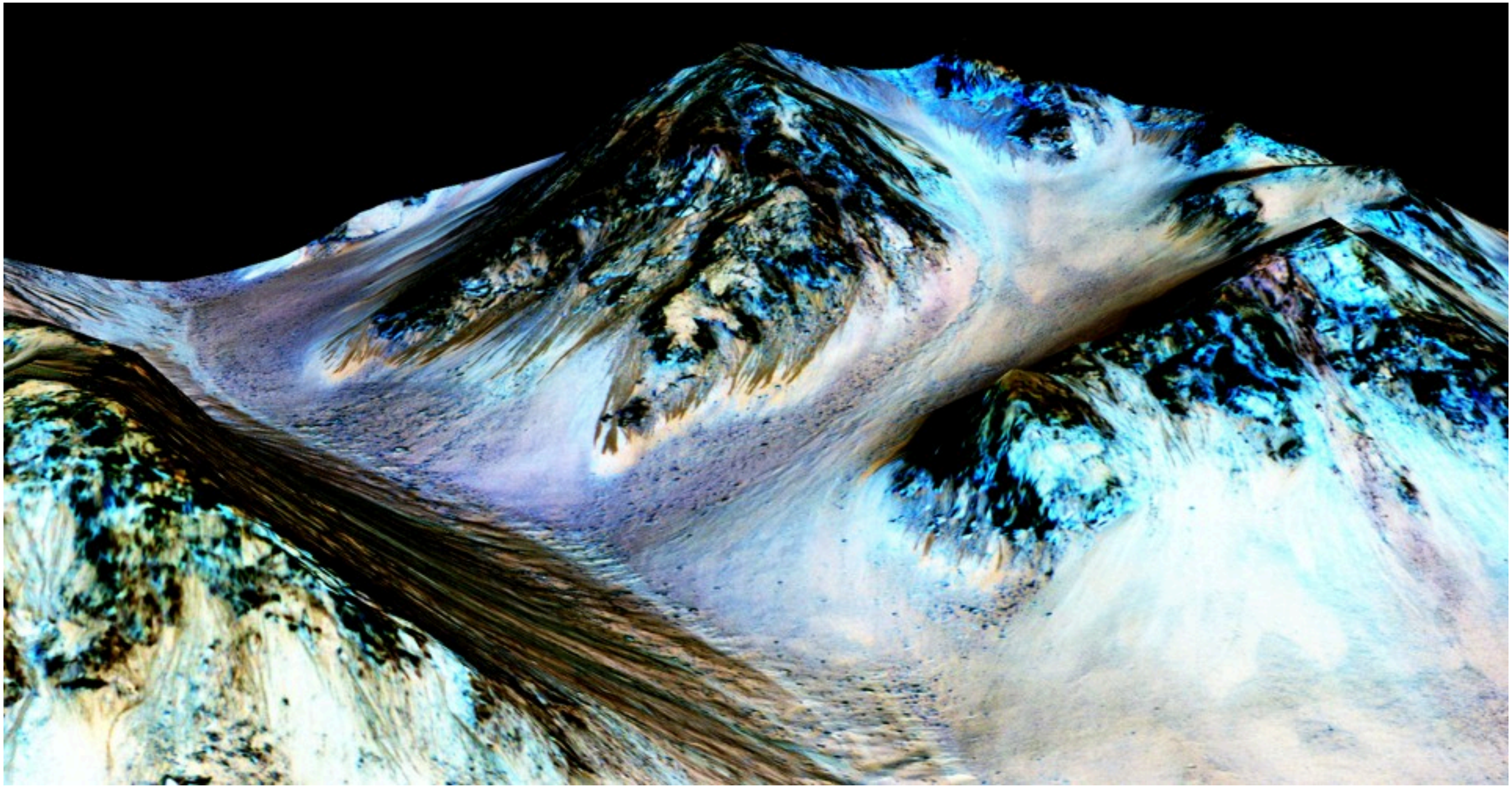


Specular reflection from Punga Mare, Titan

NRC report, “The Limits of Organic Life in Planetary Systems,” 2007

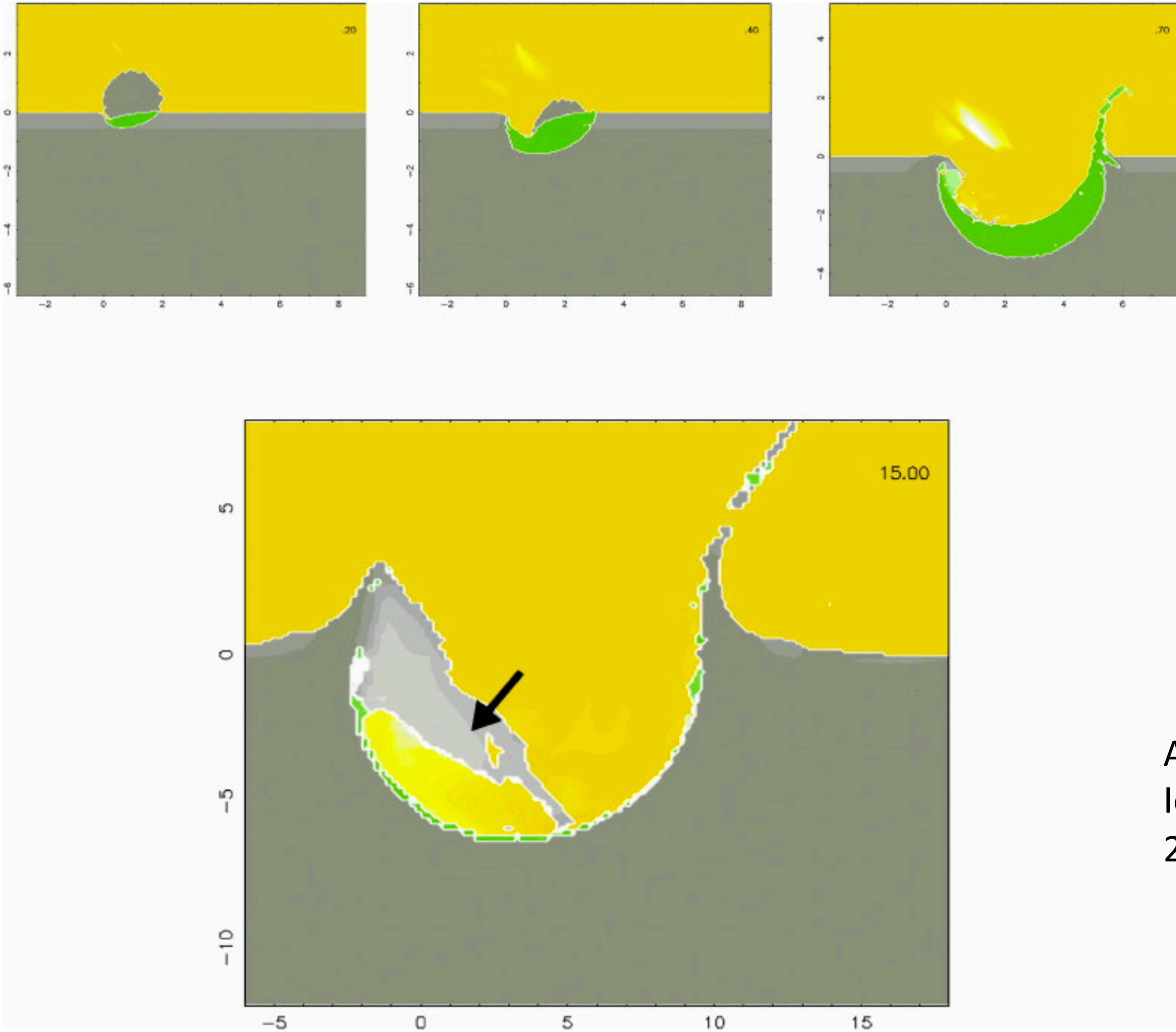
How do we know habitability when we see it?

Recurring Slope Lineae on Mars



Ojha et al Nature Geosci. 2015

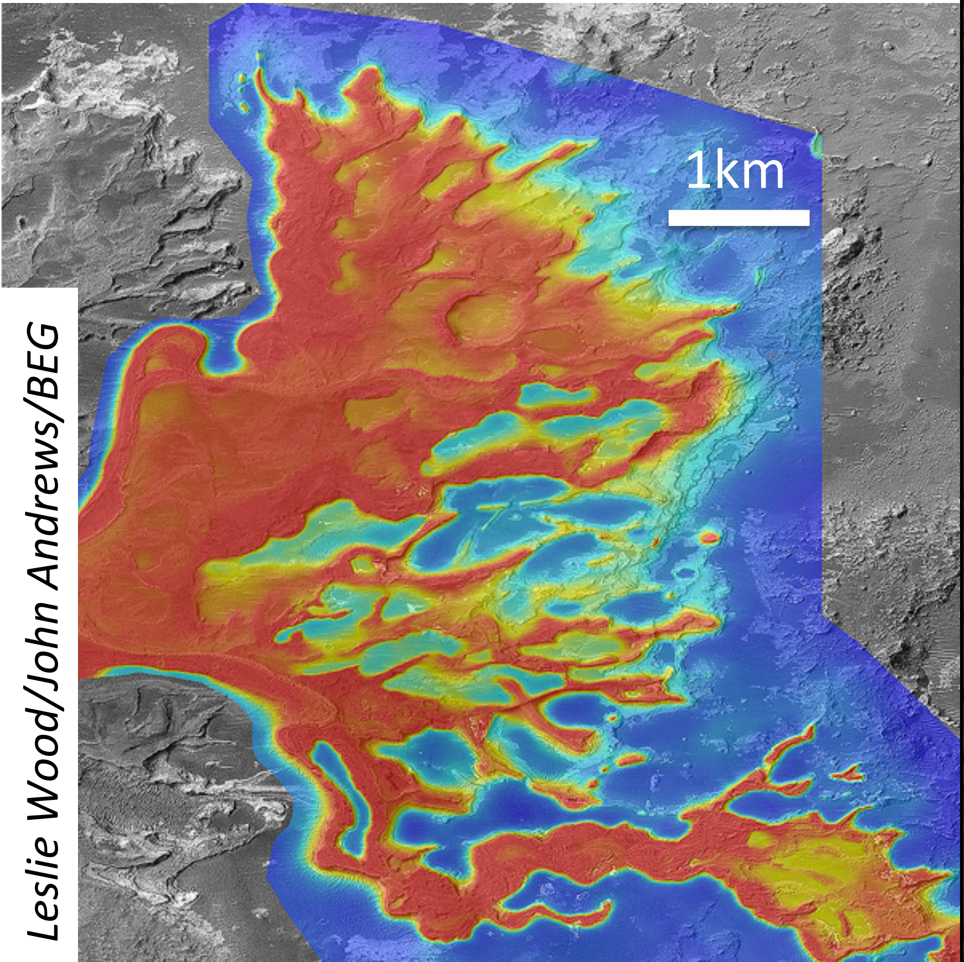
Habitable environments can be short-lived.
How short-lived is too short-lived to be interesting?



Comet impacts on Titan

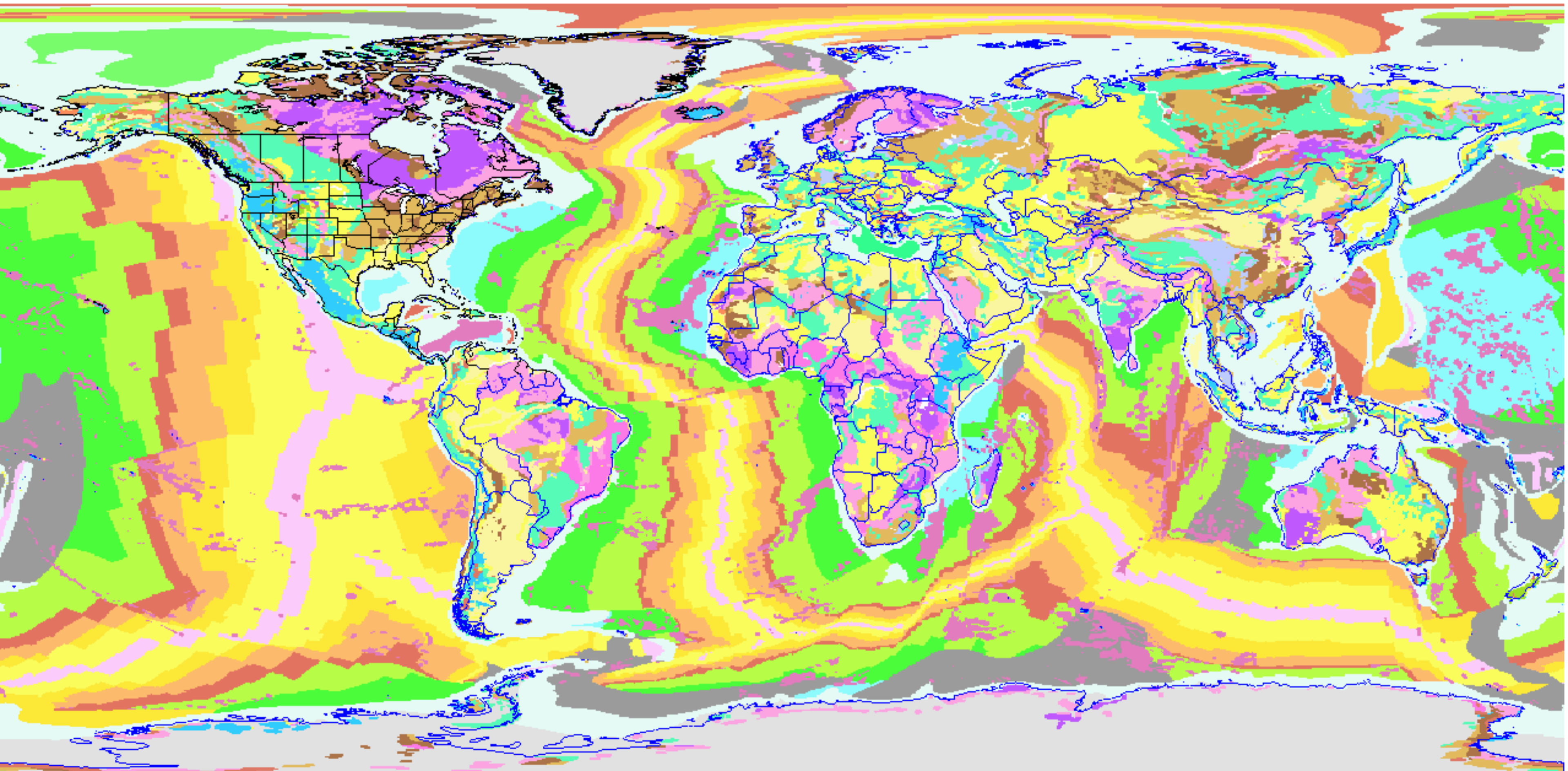
Armetieva & Lunine
Icarus
2003

If definition of habitability involves geologic timescales → geologic data needed



Earth history post-Hadean

dark purple = >2.5 Ga rocks (most have been subjected to high T/P which destroys fossils)
Plate tectonics has destroyed most of the evidence of Earth's earliest (pre-3.8 Ga) history



Carbon Isotopes

^{14}C, ^{13}C, and ^{12}C.

Organisms prefer to use ^{12}C - most abundant, most reactive, preferred by enzymes in the cell.

Biomass enriched in ^{12}C, carbonate enriched in ^{13}C.

Ratio of ^{12}C:^{13}C provides carbon isotopic fractionation value.

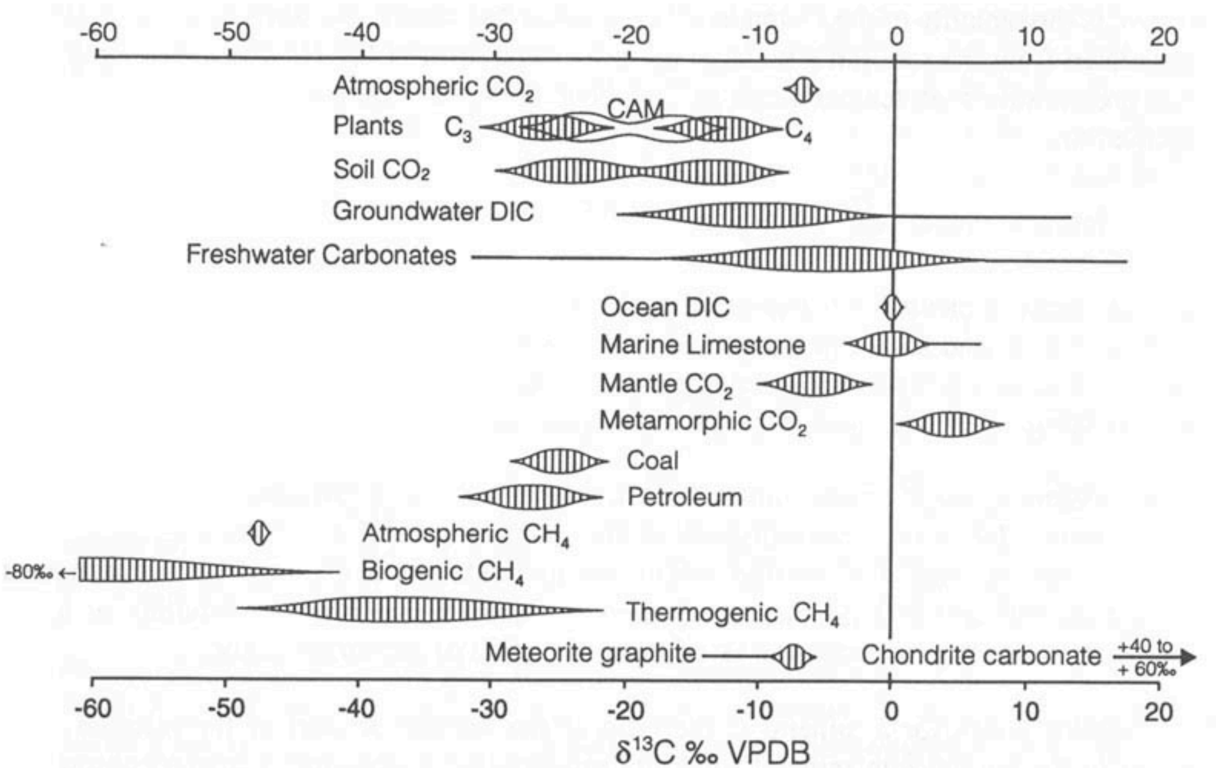


Fig. 5-1 Ranges for $\delta^{13}C$ values in selected natural compounds. Especially noteworthy is the spread in ^{13}C seen in different plant groups and the resulting soil CO_2.

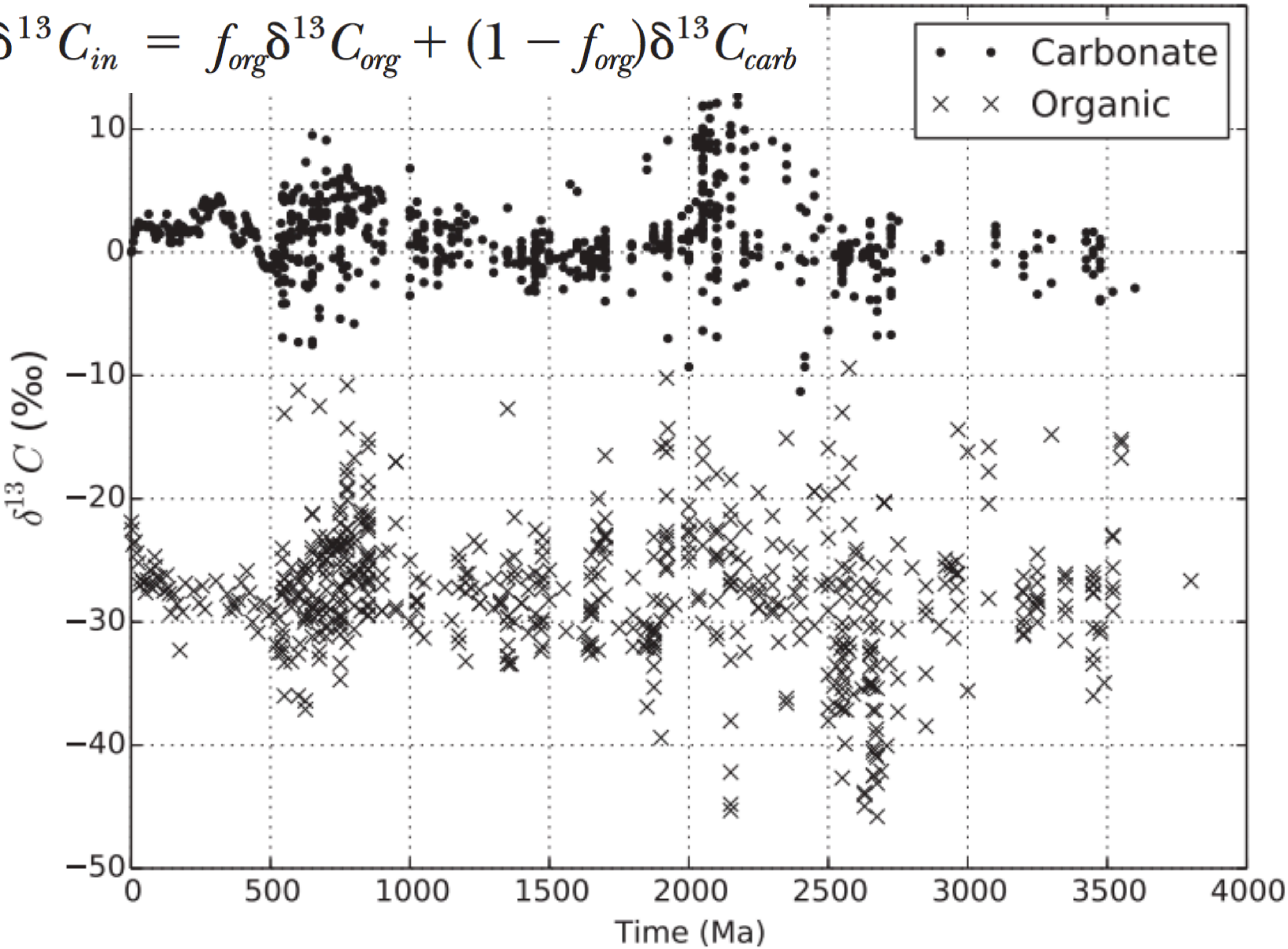
Clark & Fritz, 1997

Measured as a $\delta^{13}C$ value

$$\delta^{13}C = \frac{[^{13}C/^{12}C]_{sample}}{[^{13}C/^{12}C]_{standard}} - 1$$

‰, per mil.

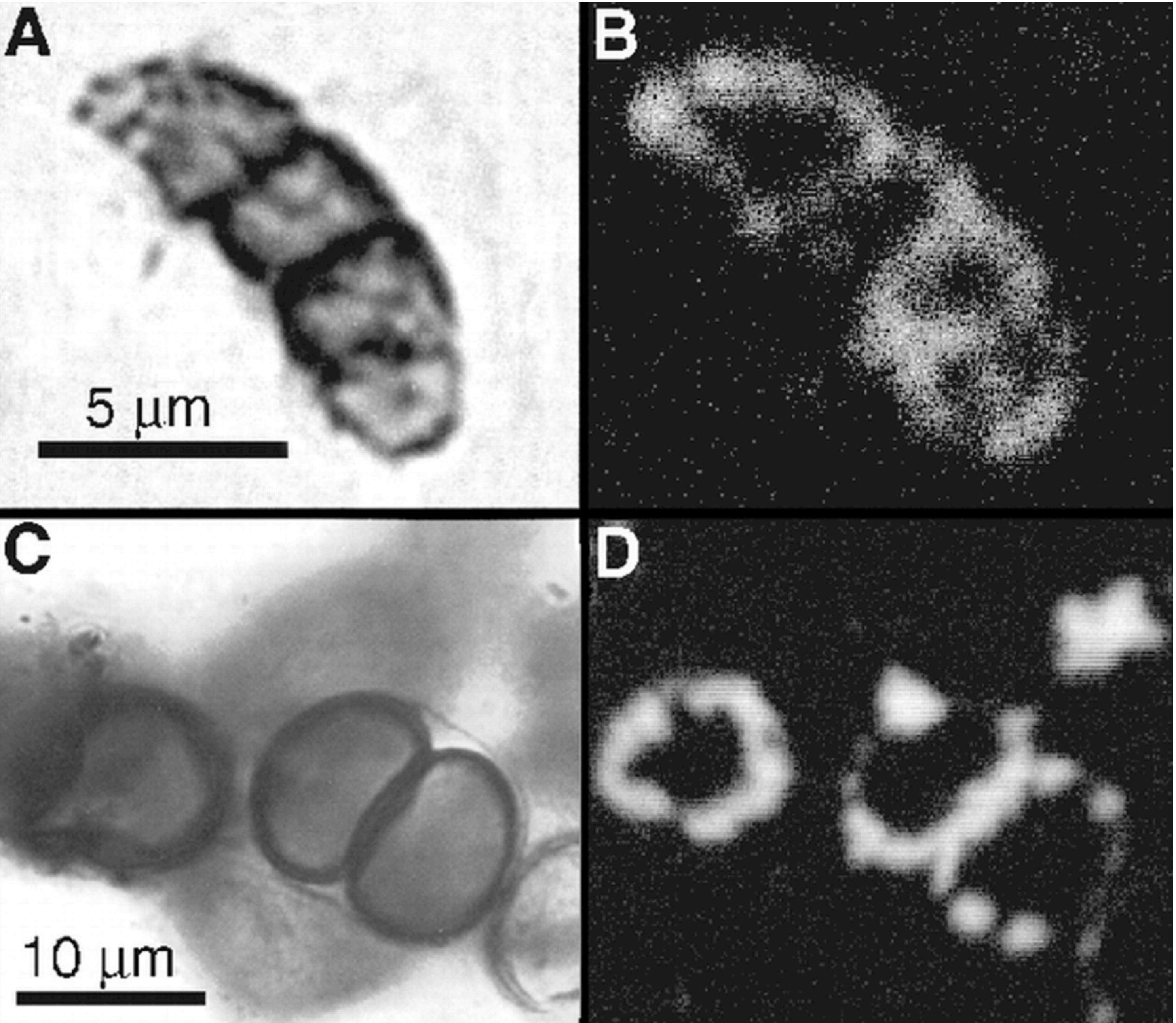
$$\delta^{13}C_{in} = f_{org}\delta^{13}C_{org} + (1 - f_{org})\delta^{13}C_{carb}$$



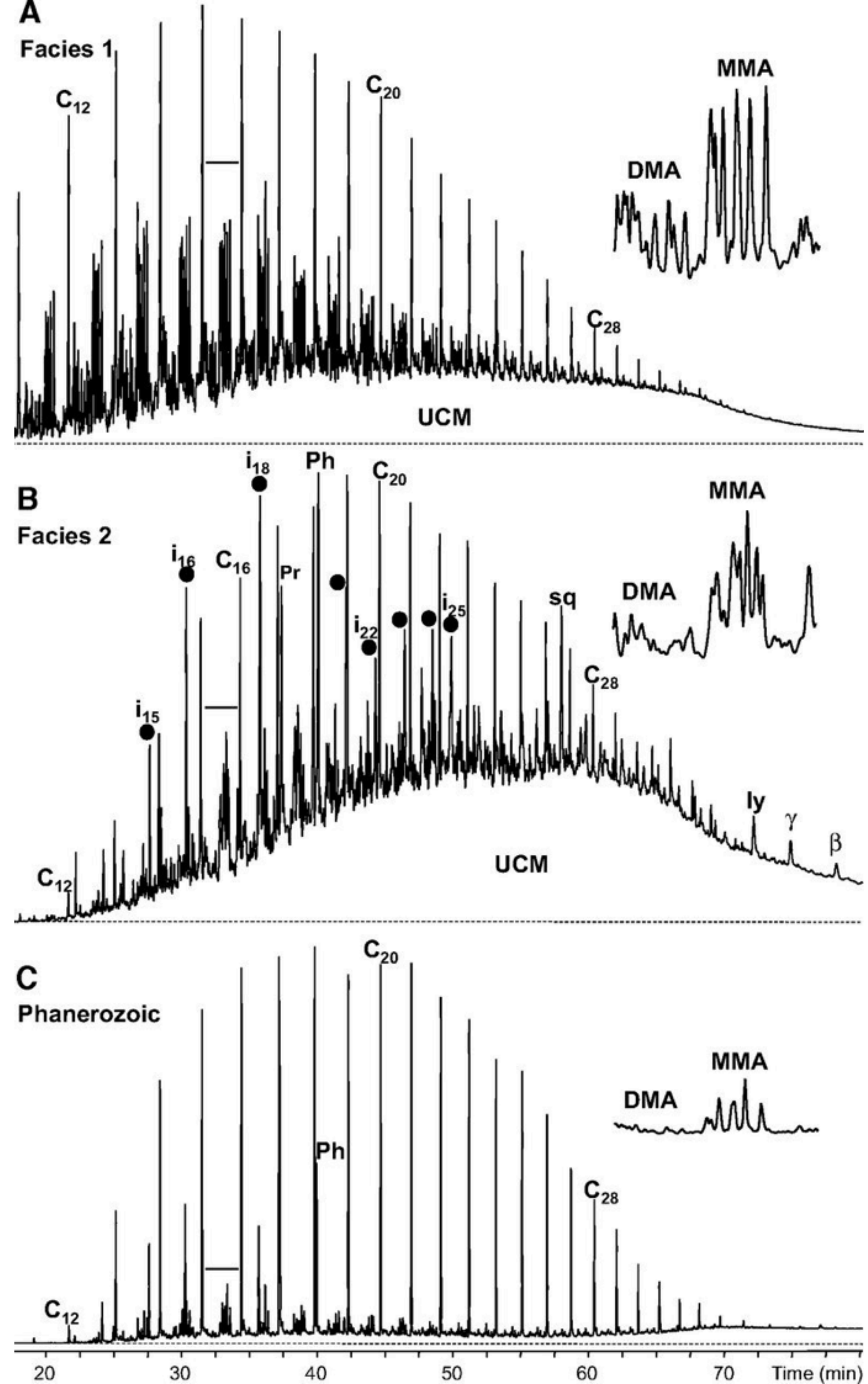
'Fundamentals of geobiology' book

Continuity of life: body fossils

1.9 Ga
Gunflint
Chert

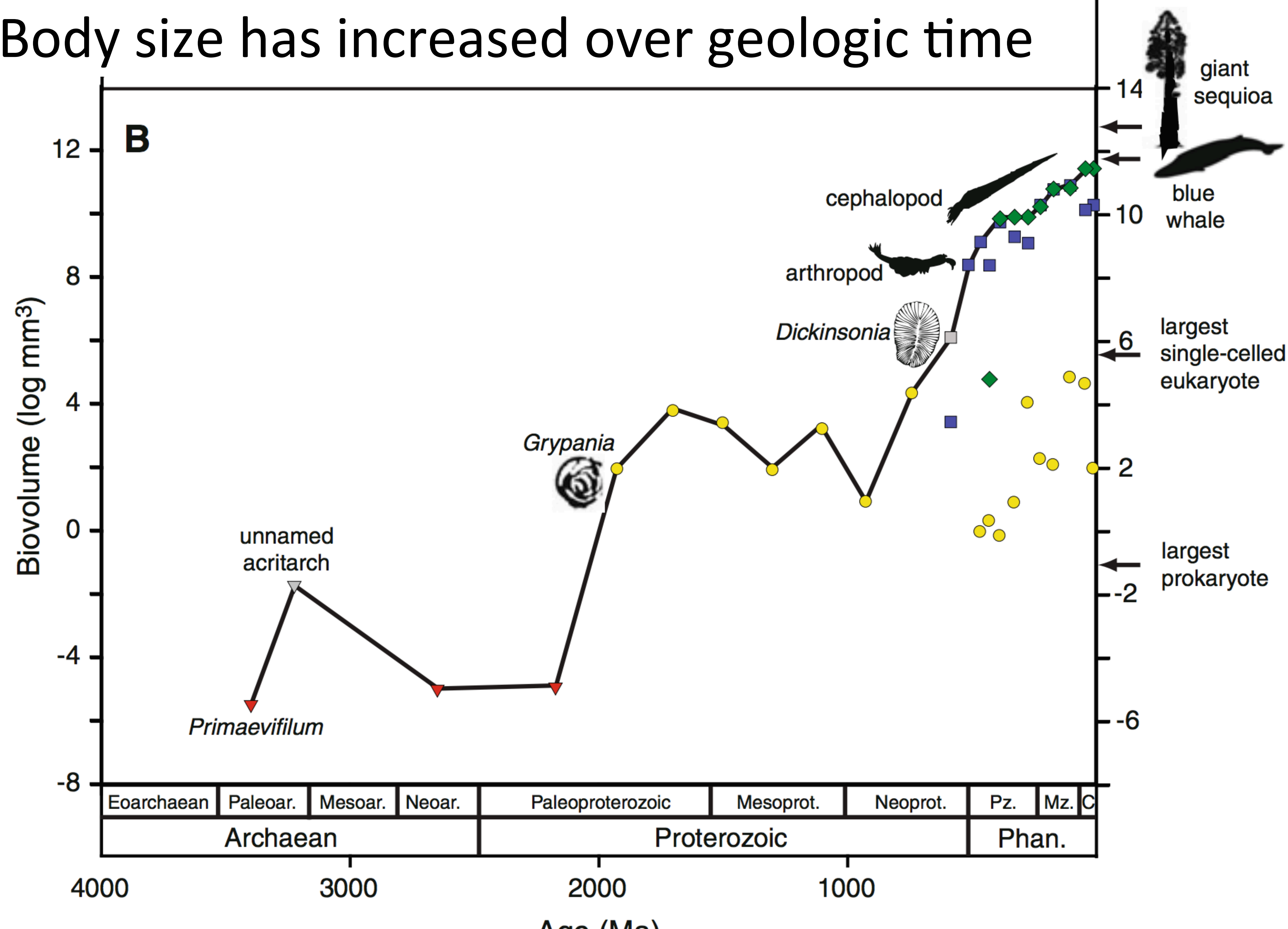


Continuity of life: Proterozoic molecular fossils



Pawloska et al. Geology 2012

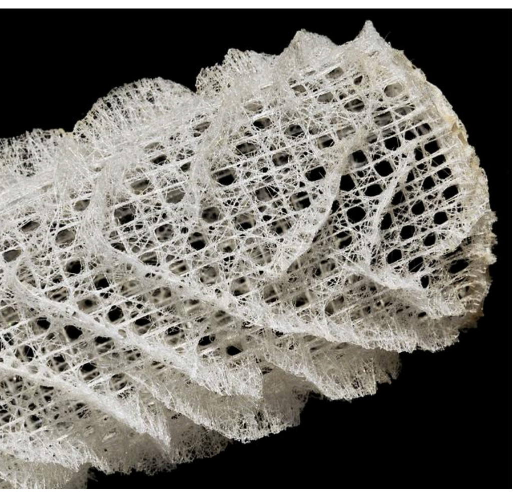
Body size has increased over geologic time



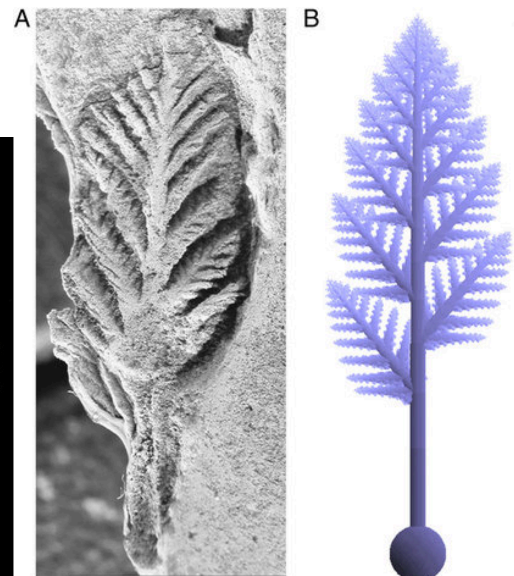
Payne et al. 2011 Photosynthesis Research


<10^8 yr increase in complexity of life in Ediacaran -> Cambrian

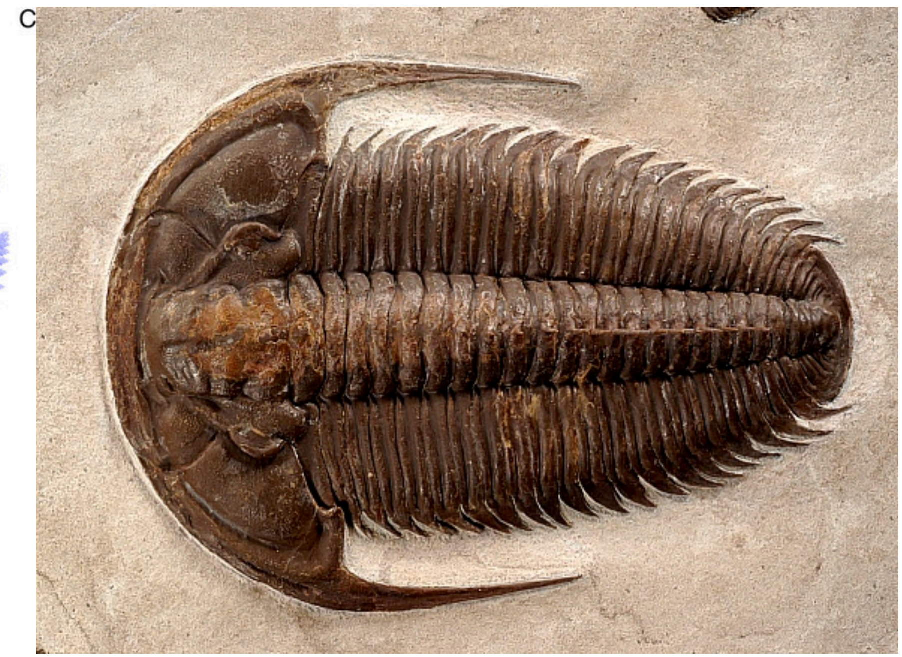
High levels of atmospheric oxygen are required for animal life



Spicules from sponges (modern sponge shown)



Rangeomorph



Yacatus

Why did the development of complex, multicellular life on Earth take so long?

- Long wait for origin of life? (very unlikely)
- Evolutionary innovations the rate-limiting step?
- Environmental changes the rate-limiting step?
- Focus for the rest of this course: <u>microbial</u> habitability

3. The remarkable coincidence between the timescale of past biological evolution on Earth and the future life expectancy of the Sun

The coincidence to which I am referring is based on the very well known fact (see, for example, Dickerson & Geiss 1976) that the time t_e, say, that has been taken so far by biological evolution on this planet since its formation is given to within a few tens of percent by

$$t_e \approx 0.4 \times 10^{10} \text{ years} \tag{3.1}$$

and the almost equally well known fact (see, for example, Hoyle 1955) that the 'main sequence' lifetime, τ_0 say, of the Sun, during which the energy output from steady hydrogen burning can maintain favourable conditions for life on Earth, is estimated to be given with not quite comparable precision by

$$\tau_0 \approx 10^{10} \text{ years.} \tag{3.2}$$

Now the biological processes that have governed the evolution of life up to the present stage of emergence of civilization and the astrophysical processes determining the lifetime of the Sun have nothing directly to do with each other (the slowness of the former arising from the numerical complexity of living systems, whereas the slowness of the latter arises from the weakness of gravitation). Therefore the coincidence of these numbers to within a factor close to two, representing the observation that the Sun is now just about half way through its expected life, does not deserve to be just taken for granted as it seems to have been until now. (Indeed, simply in terms of precision, this coincidence is much more striking than the order of magnitude cosmological coincidences which not unjustifiably caught the attention of Dirac.)

Carter 1983
Phil. Trans.

Possible responses to Carter's argument include:

(A) It is a very powerful argument that uses only a few unobjectionable assumptions,

(B) One bit of data is worth more than a hundred pages of this kind of argument.

What can we infer about climate from the continuity of life?

<u>Continuous surface (or near-surface) liquid water</u>

Life is known to proliferate at least within this range:

T = -25C to 122C

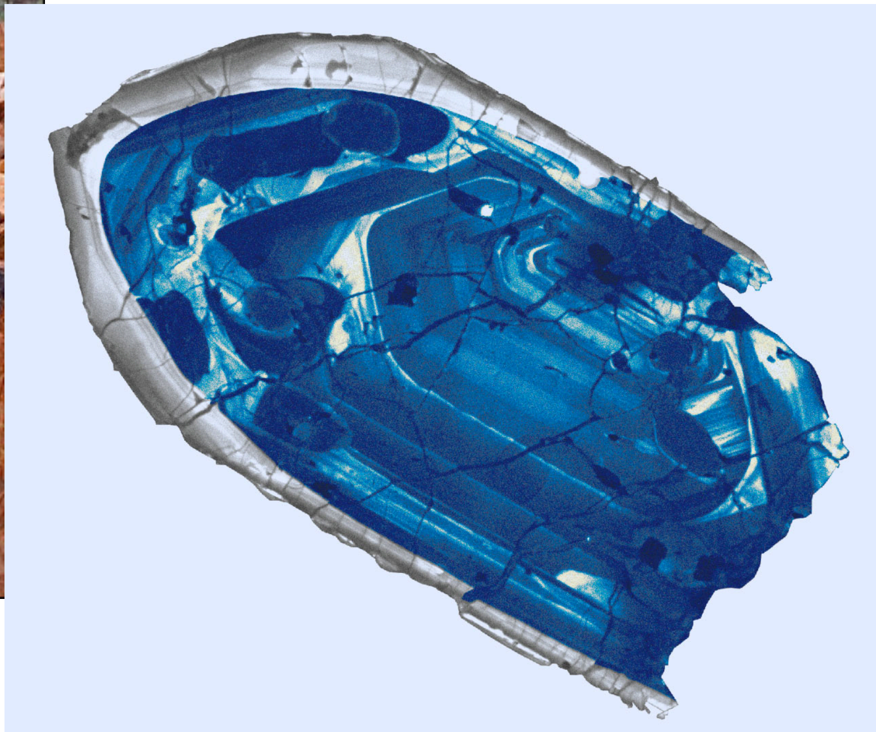
pH = 0 to 13

P up to 200 MPa

Water activity as low as 0.6

Searching for Life Across Space and Time: Proceedings of a Workshop, 2017

Evidence for oceans on Earth >4.0 Ga



Jack Hills zircons

Glaciation uncommon in Earth history

History of Earth’s climate

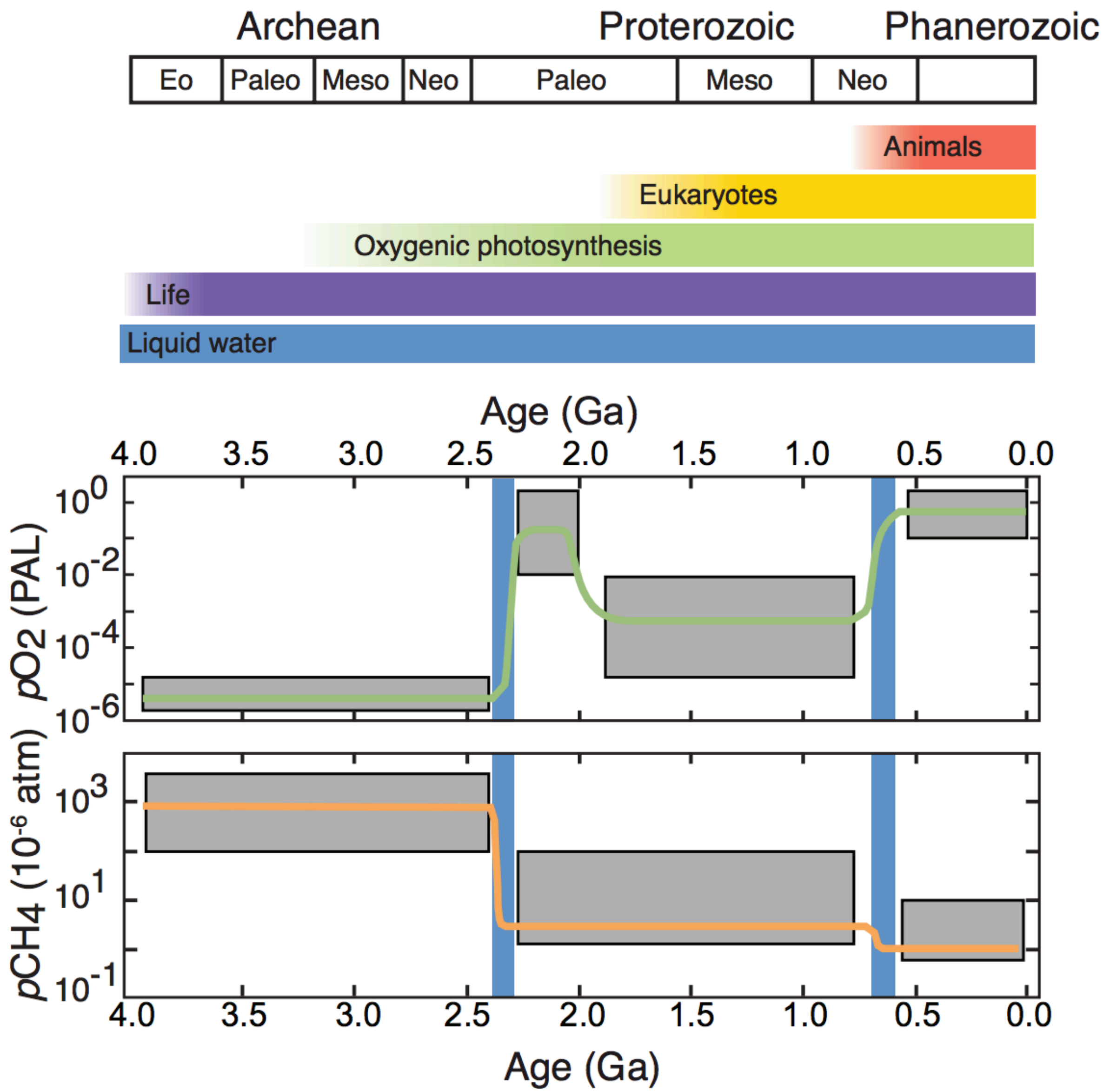


Figure 2. *Co-evolution of life and surface environments on Earth*. The top panel shows the timing of major transitions in the history of the biosphere. The middle panel shows Earth's oxygenation trajectory, while the bottom panel shows the abundance of CH_4 through time. In each, the vertical blue bars denote the timing of low-latitude glaciations, while colored lines show one possible trajectory through the parameter space implied by proxy reconstructions (shaded boxes; see **Fig. 1** and **Fig. 3b**).

Stephanie Olson et al., 2018

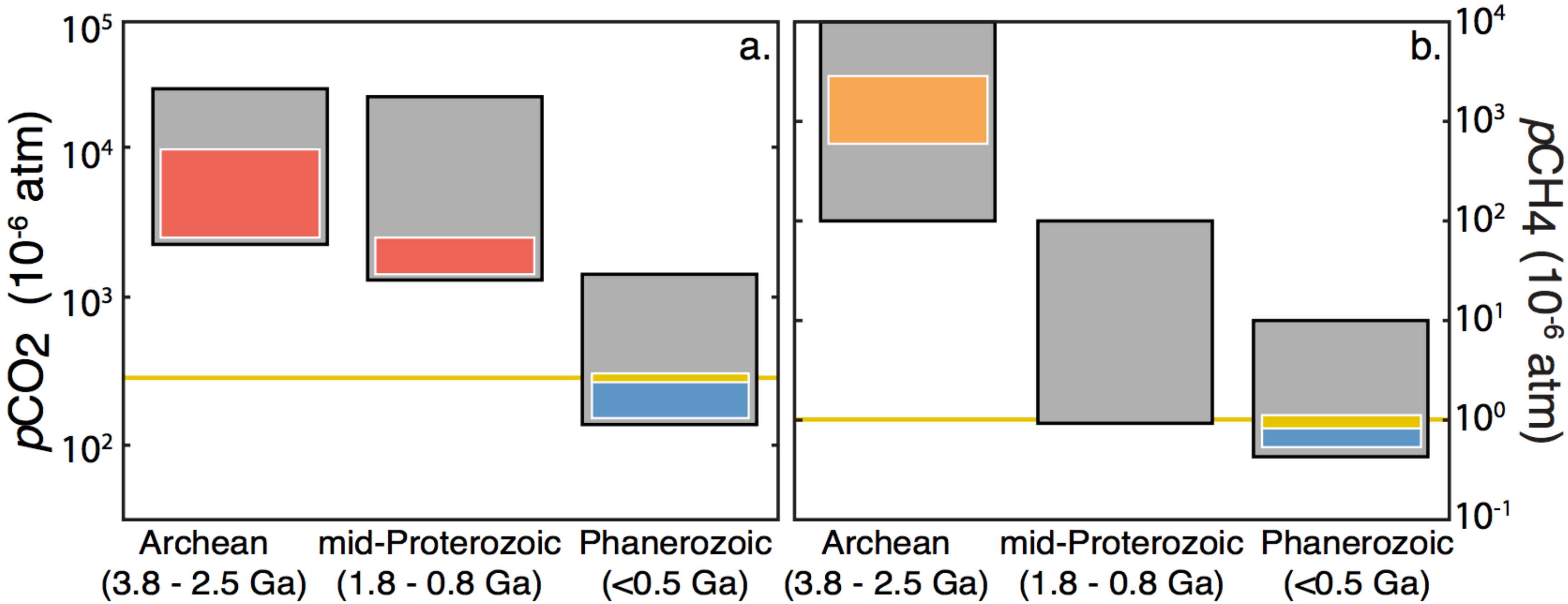


Figure 3. *Greenhouse constraints through Earth history.* For each geological eon, grey boxes represent inclusive ranges for model and proxy-based constraints on atmospheric pCO_2 (**a**) and pCH_4 (**b**). The minimum and maximum values for each grey box are specified in **Table 3** for CO_2 and **Table 4** for CH_4. The colored bars represent preferred ranges corresponding to constraints from specific proxies discussed in the text, including: paleosols (red), organic haze (orange), ice core records (for the last 800,000 years (Loulergue et al 2008; Luthi et al 2008); light blue), and Mauna Loa observations (since 1958 for CO_2 (*e.g.*, Keeling 1976) and since 1983 for CH_4 (Dlugokencky et al 1994); yellow).

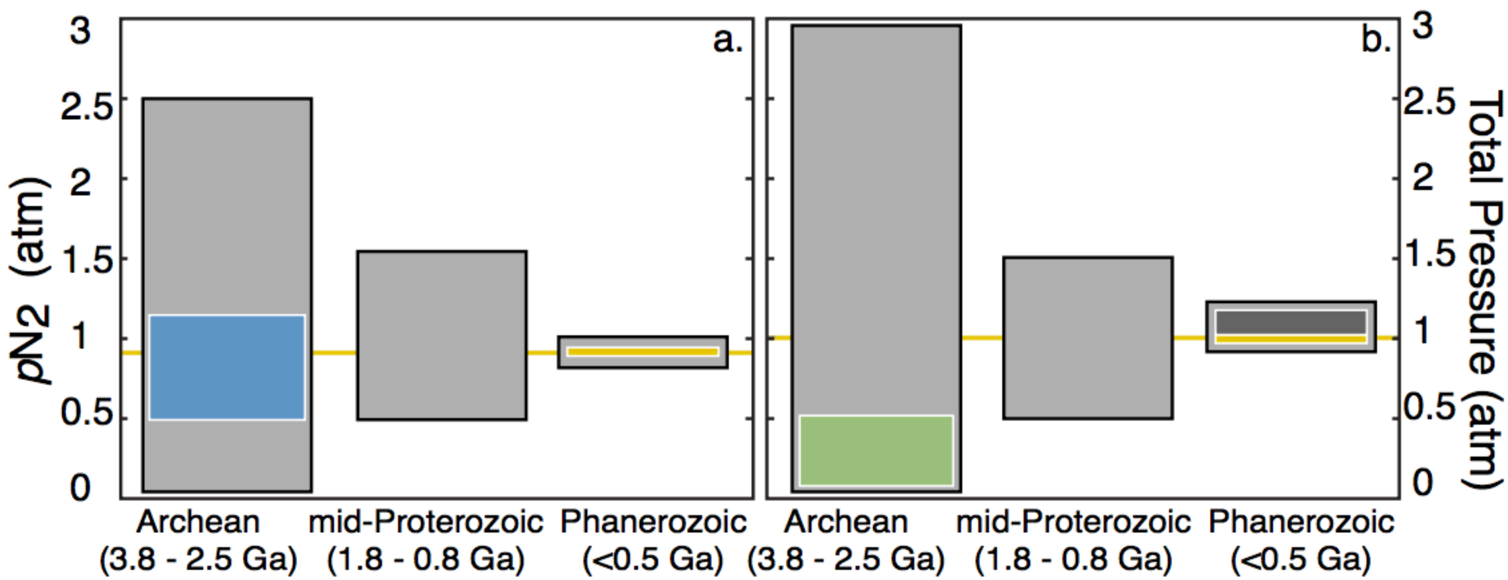


Figure 4. *N_2 and pressure constraints through Earth history*. For each geological eon, grey boxes represent inclusive ranges for model and proxy based constraints on pN_2 (**a**) and total atmospheric pressure (**b**). The colored bars represent preferred ranges corresponding to constraints from specific proxies discussed in the text, including: N isotopes (blue), basalt vesicles (green), and ice core records (light blue). As elsewhere, yellow line denotes modern pN_2 and total pressure. Total pressure generally tracks N_2 abundance, but the dark grey box in (**b**) represents elevated surface pressure due to very high O_2 during the Carboniferous (see **Fig. 1a**). In the Archean, the apparent incompatibility of pN_2 and total pressure constraints may be reconciled by considering the temporal separation between the pN_2 constraints (3.5-3.0 Ga; Marty et al 2013) and the total pressure constraints (2.7 Ga; Som et al 2016); these complementary datasets may suggest a secular decline in atmospheric pressure during the Archean eon (*e.g.*, Stüeken et al 2016).

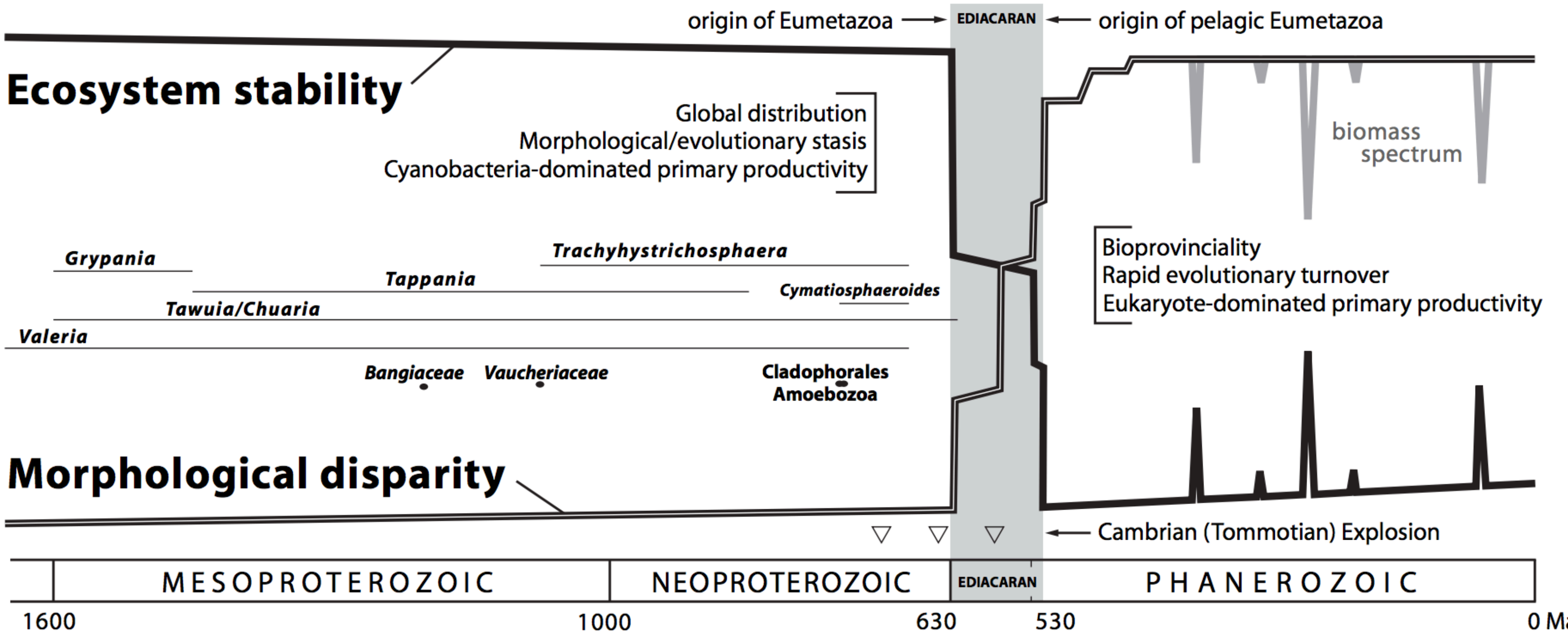
Stephanie Olson et al., arXiv 2018

Next lecture: why has Earth avoided the fates of Mars and Earth?

http://geosci.uchicago.edu/~kite/geos32060_2019/

Bonus slides

Complex life and complex biospheres are lacking for most of Earth history



TEXT-FIG. 1. A conceptual view of the macroecological differences between the pre-Ediacaran and post-Ediacaran marine biospheres, and the transitional Ediacaran. The disparity curve is derived from acritarch data and estimated number of cell types (McShea 1996; Huntley *et al*. 2006), and ecosystem stability from estimated rates of evolutionary turnover (Sepkoski 1984; Knoll 1994). The spikes in ecosystem stability following Phanerozoic mass extinctions are inferred from observed and modelled recovery times (Solé *et al*. 2002). Biomass spectrum very broadly tracks disparity through this interval (see Bell and Mooers 1997) except during mass extinctions, which are characterized by the loss of large organisms but not cell types. Also shown are the age ranges of pre-Ediacaran eukaryotes discussed in the text, and the Cryogenian and Ediacaran glaciations (triangles). Note that the Ediacaran/Cambrian boundary as depicted here (at the base of the Tommotian; *c*. 530 Ma) differs from the IUGS-ratified position, which corresponds to the base of the preceding Nemakit-Daldyn Stage (*c*. 542 Ma). Vertical scale for all curves is qualitative only.

Nick Butterfield, Macroevolution and macroecology through deep time, Paleontology, 2007

Using genetic data to probe paleoclimate? ***new, little-tested method***

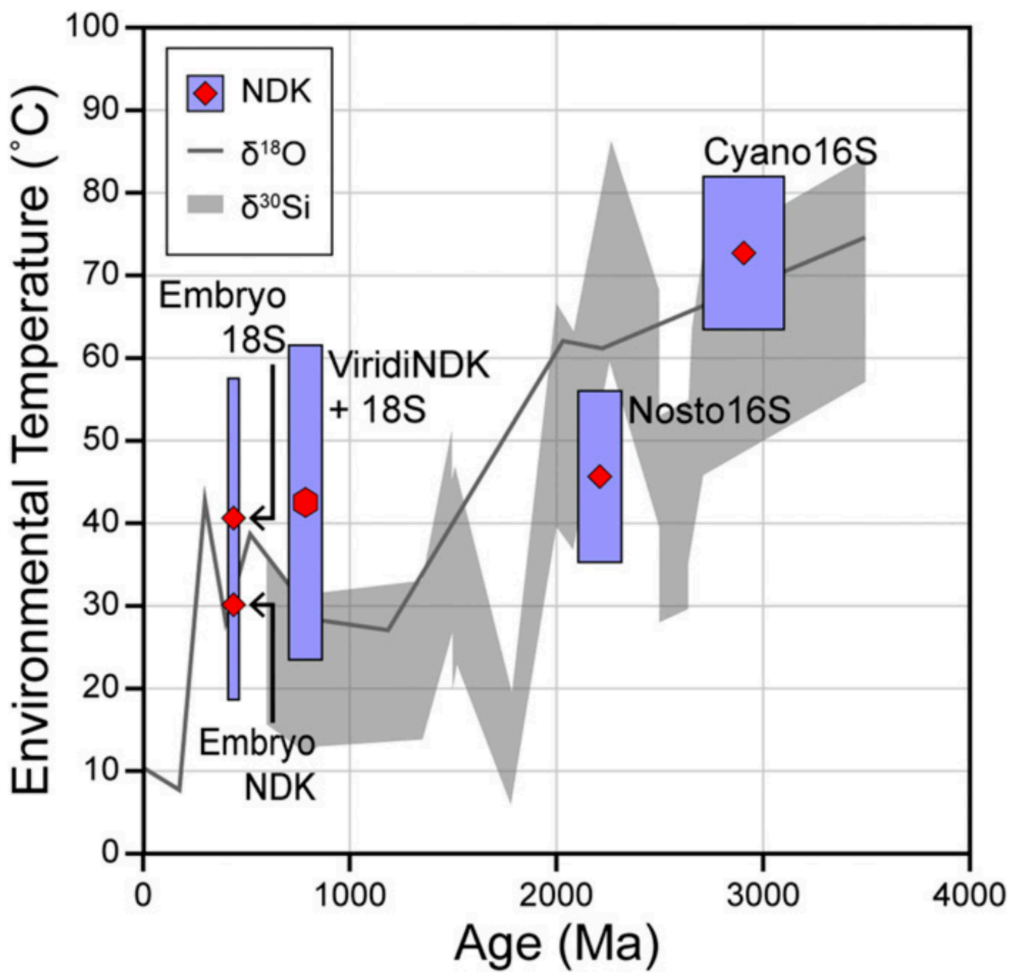


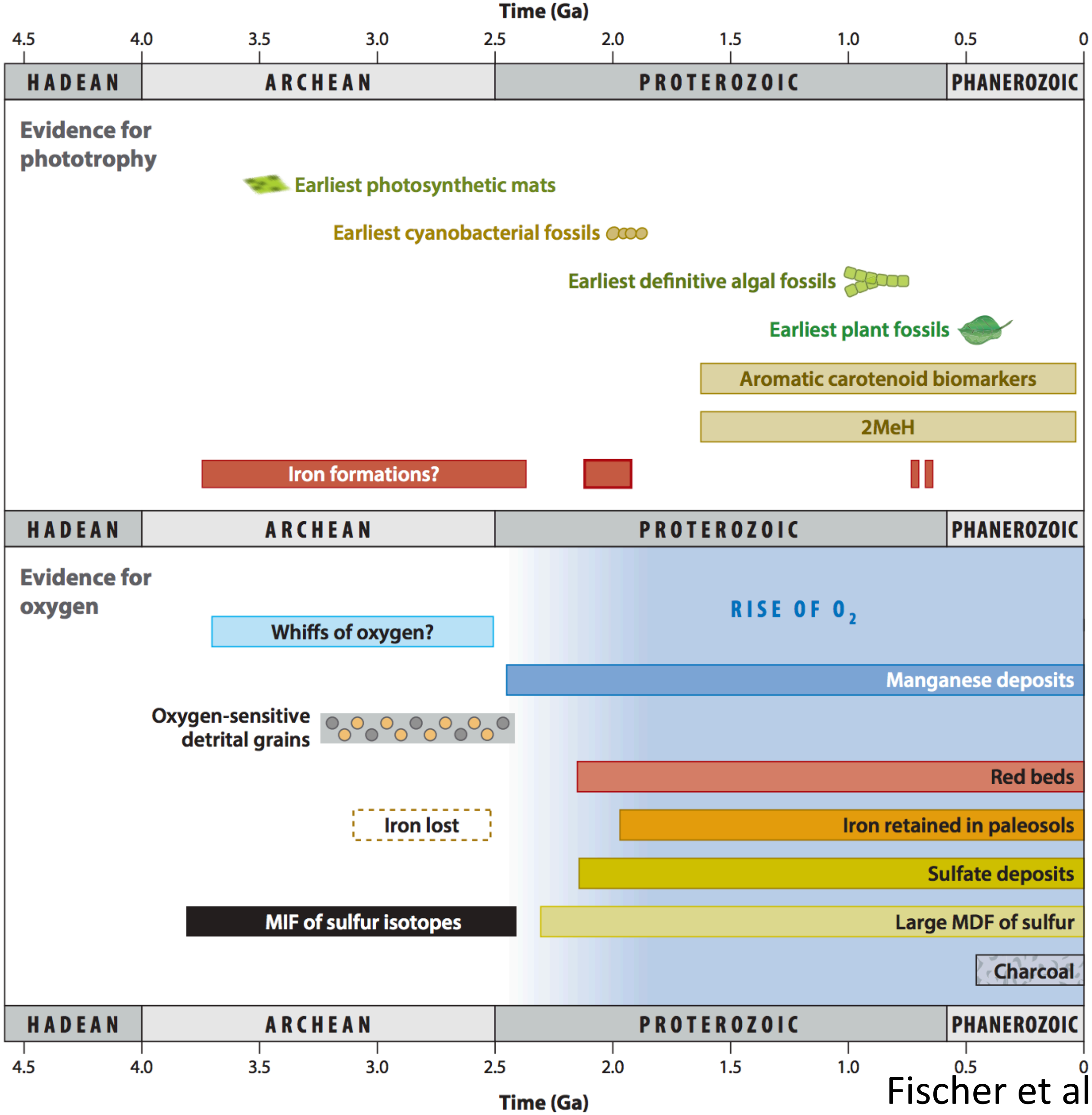
Fig. 4. Environmental temperature ranges inferred from reconstructed ancestral NDK T_ms plotted against fossil-record-indicated first appearance of the various groups. Paleotemperatures inferred from $\delta^{18}O$ (5) and $\delta^{30}Si$ (7) in marine cherts are included for comparison. Blue boxes show the inferred NDK-based temperature ranges (Fig. 3) and fossil-based age uncertainties, the red diamonds denoting temperature and age midpoint values for which ViridiNDK and Viridi18S have been combined due to the similarity of their T_ms.

- Resurrect ancestral proteins
- Determine their temperature sensitivity

NDK = nucleoside diphosphate kinases

Garcia et al. PNAS 2017

Origin of oxygenic photosynthesis



Fischer et al., Annual Reviews, 2016

Table 1. Atmospheric O_2 constraints for each geologic eon

Eon		**Constraints** (xPAL)		**Notes**
		Min.	*Max.*	
Archean		10^{-12}	10^{-5}	The minimum estimate arises from abioitic photochemical production of O_2 (1); the maximum derives from the persistence of MIF-S (2), but transient excursions to higher pO_2 (3) are allowed (4).
mid-Proterozoic	*Incl.*	10^{-5}	10^{-1}	The minimum is constrained by absence of MIF-S (2); the maximum is likely constrained by the absence of Cr isotope fractionation (5), but is difficult to reconcile with photochemical models (6).
	Pref.	10^{-5}	10^{-3}	
Phanerozoic		10^{-1}	2	The minimum and maximum values here reflect temporal variability rather than ambiguities in proxy interpretation as above (7).

By convention, pO_2 is expressed with respect to the present atmospheric level (PAL) of O_2: 0.21 atm. Minimum and maximum values are provided for inclusive and preferred ranges where divergent constraints exist. Inclusive ranges correspond to the grey boxes in ***Fig. 1*** *whereas preferred ranges are highlighted with colored boxes. The numbered references within the table correspond to: (1) Kasting et al 1979; (2) Pavlov and Kasting 2002; (3) Anbar et al 2007; (4) Reinhard et al 2013b; (5) Planavsky et al 2014b; (6) Claire et al 2006; (7) Berner 1999.*

Stephanie Olson et al., arXiv 2018

Table 3. Atmospheric CO_2 constraints for each geologic eon

Eon	Constraints (µatm)			Notes
		Min.	*Max.*	
Archean	*Incl.*	2500	40000	The inclusive minimum and maximum constraints come from river gravels and paleosols, respectively (1, 2). The likely maximum reflects a refined paleosol constraint using updated methodology (3). The range in pCO_2 results from ambiguities in proxy records as well as secular decline (4).
	Pref.	2500	15000	
mid-Proterozoic	*Incl.*	1400	28000	The minimum value reflects a minimum reported upper estimate rather than a true lower bound (5); the inclusive maximum value is inferred from microfossil morphology (6) whereas the likely maximum is derived from paleosols (7). The range results from ambiguities in proxy records as well as secular decline.
	Pref.	1400	2800	
Phanerozoic		200	2800	The Phanerozoic CO_2 history is well constrained (8); the range of values presented here reflects temporal variability in pCO_2. Despite a nonlinear trajectory, this record is broadly compatible with secular decline since the Archean (4).

*Here pCO_2 is expressed in units of uatm as plotted in **Fig 3**, whereas paleo-pCO_2 constraints are often expressed as a multiple of the pre-industrial atmospheric level (PAL) in the Precambrian literature and/or ppmv in the more recent past. We have converted to µatm from PAL assuming pCO_2 = 280 µatm, unless otherwise specified by the original authors. Note that in the recent past for which total pressure has been 1 atm, 1 µatm is synonymous with 1 ppmv—but this equivalence is invalid for most of Earth history because total atmospheric pressure has changed substantially (see **Fig. 4b**) and we have thus avoided use of ppmv here. Minimum and maximum values are provided for inclusive and preferred ranges where divergent constraints exist. Inclusive ranges correspond to the grey boxes in **Fig. 3a** whereas preferred ranges are highlighted with colored boxes. The numbered references within the table refer to: (1) Hessler et al 2004 (2) Rye et al 1995; (3) Sheldon 2006; (4) Walker et al 1981; (5) Mitchell and Sheldon 2010; (6) Kaufman and Xiao 2003; (7) Sheldon 2013; (8) Royer et al 2004.*

Stephanie Olson et al., arXiv 2018

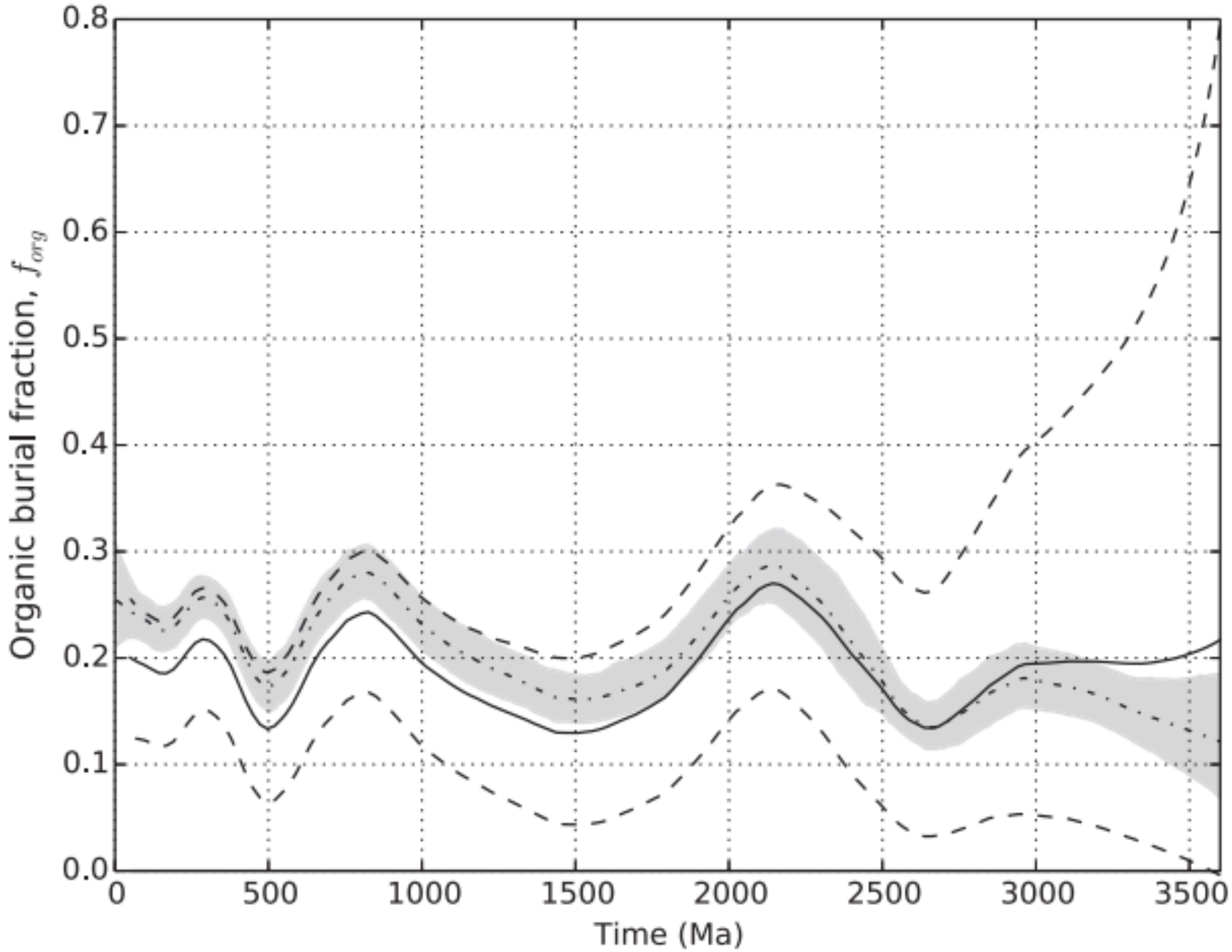


Fig. 6. Smoothed f_{org} (solid line) with 95% confidence intervals (dashed lines) from the updated carbon cycle model and parameter distributions described in the main text. Smoothed f_{org} from the simple carbon cycle model using LOWESS (section 4.1) is denoted by the dot-dash line for comparison, with 95% confidence intervals shaded gray.

Krissansen-Totten et al. Am. J. Sci. 2015