The potential role of meteorites (and meteorite impacts) in the origin of life on Earth (and elsewhere?)

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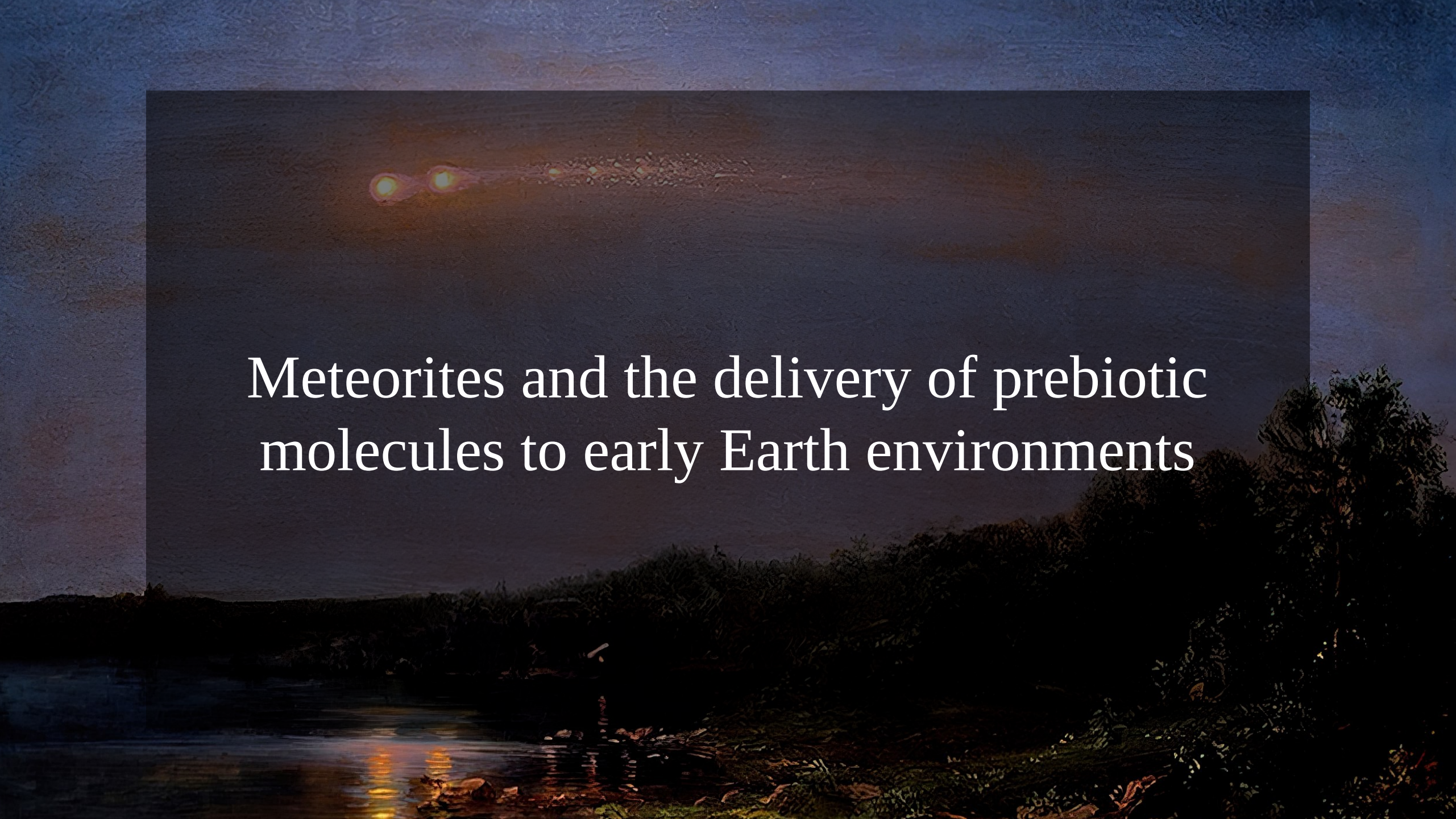


Meteorites and the delivery of prebiotic molecules to early Earth environments

Review Article | Published: 09 January 1992

Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: an inventory for the origins of life

Christopher Chyba & Carl Sagan

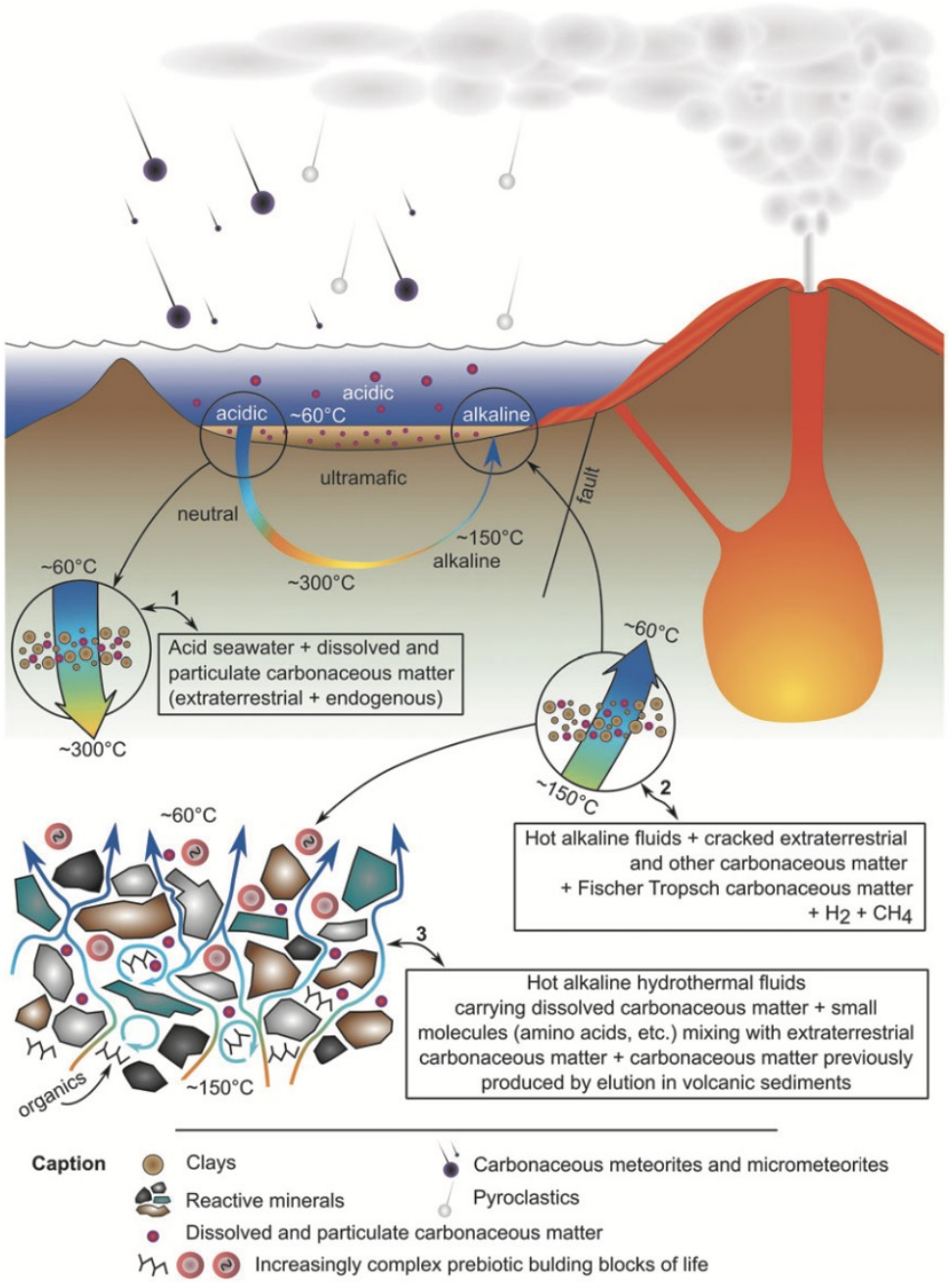
Nature **355**, 125–132 (1992) | Cite this article

Endogneous production

– Earth possessed all the necessary ingredients and environmental conditions for life?

Exogenous delivery

– Earth did not possess all the necessary ingredents (or environments?) for life.



Meteoritic influx to early Earth environments

- Relatively uninterrupted flow of meteorites and micrometeorites throughout Earth history that was most pronounced in early Earth history.

- Late Heavy Bombardment? Whether a cataclysmic and deleterious event < 300 Ma (Cohen et al., 2000, *Science*) or a prolonged and less impactful influence over > 1 Ga (Zellner et al., 2017, *OLEB*), extraterrestrial inputs to early Earth environments were significant.

- Molecules of plausible importance to prebiotic chemistry are known to be delivered to Earth by meteorites (Schmitt-Kopplin et al., 2010, *PNAS*; Oba et al., 2020, *Nature Communications*); King et al. (2022, *Science Advances*).

Westall et al. (2018, *Astrobiology*)

How to concentrate prebiotic molecules on the early Earth?

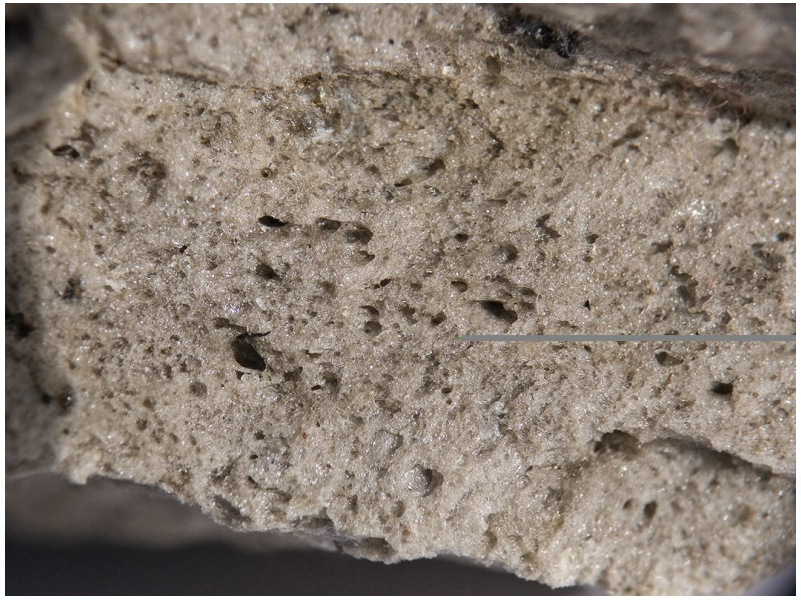
- The early Earth was a dominantly oceanic planet, possibly with limited subaerial exposure until the early Archaean.

- Subaerial environments too short-lived and susceptible to destruction to concentrate prebiotic molecules over ‘prebiotically relevant timescales’ to play a role in OOL.

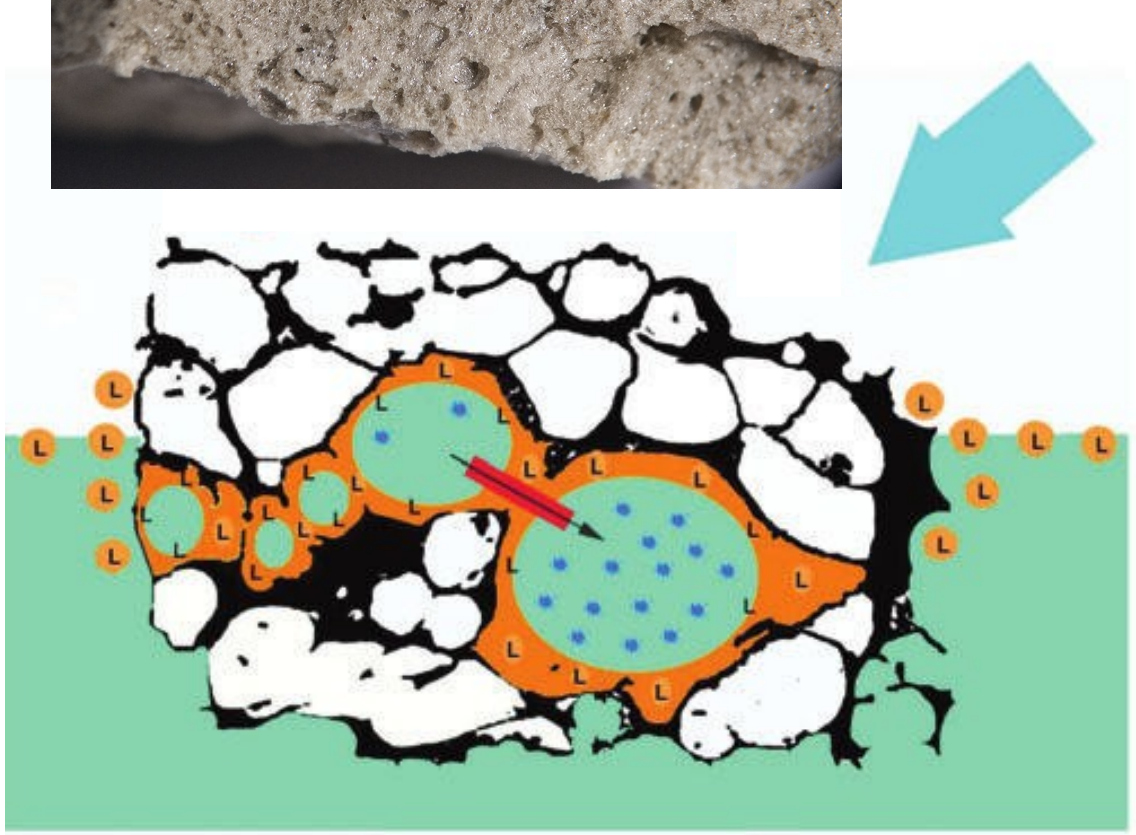
- Coastlines too sporadic to play a role in OOL.

- Hydrothermal systems known to be widespread and plausibly played a role in OOL, but may not have produced the total complement of molecules needed for OOL.

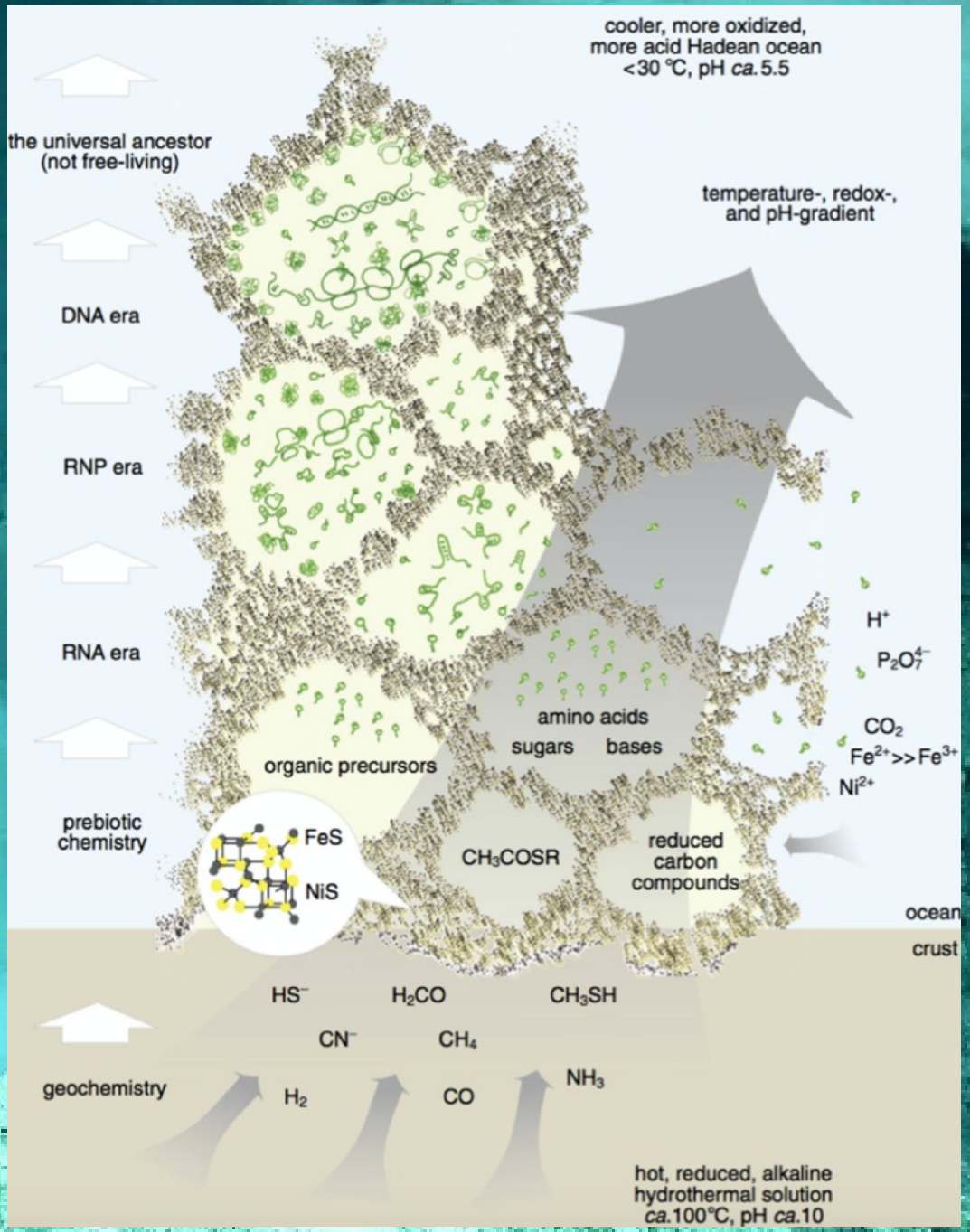
The pumice hypothesis

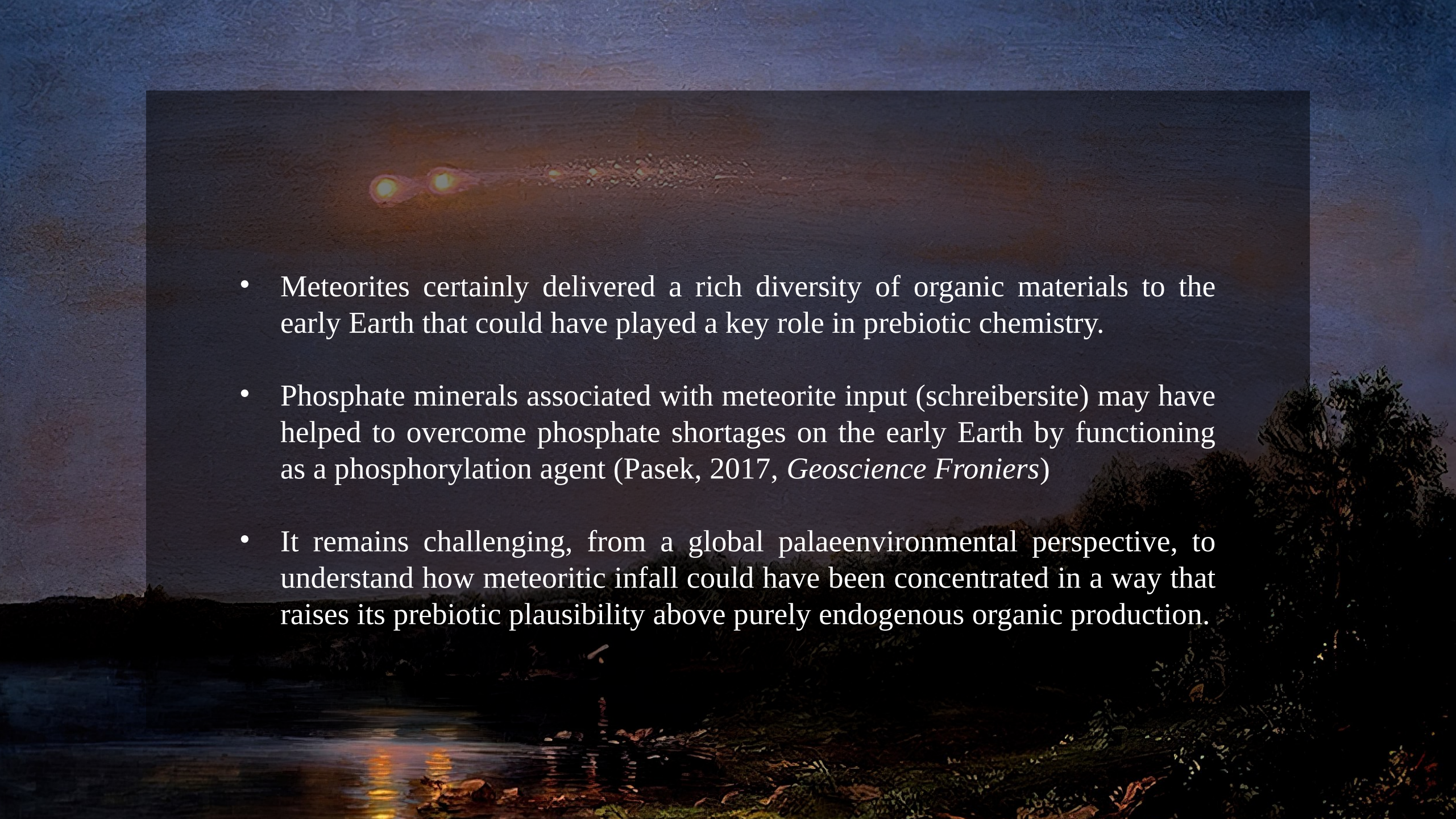


- '*Natural reactor flask*' for prebiotic chemistry.
- Concentrates prebiotic materials (e.g. molecules delivered by meteoritic infall) over prebiotically relevant timescales?



Brasier et al. (2011, *Astrobiology*)

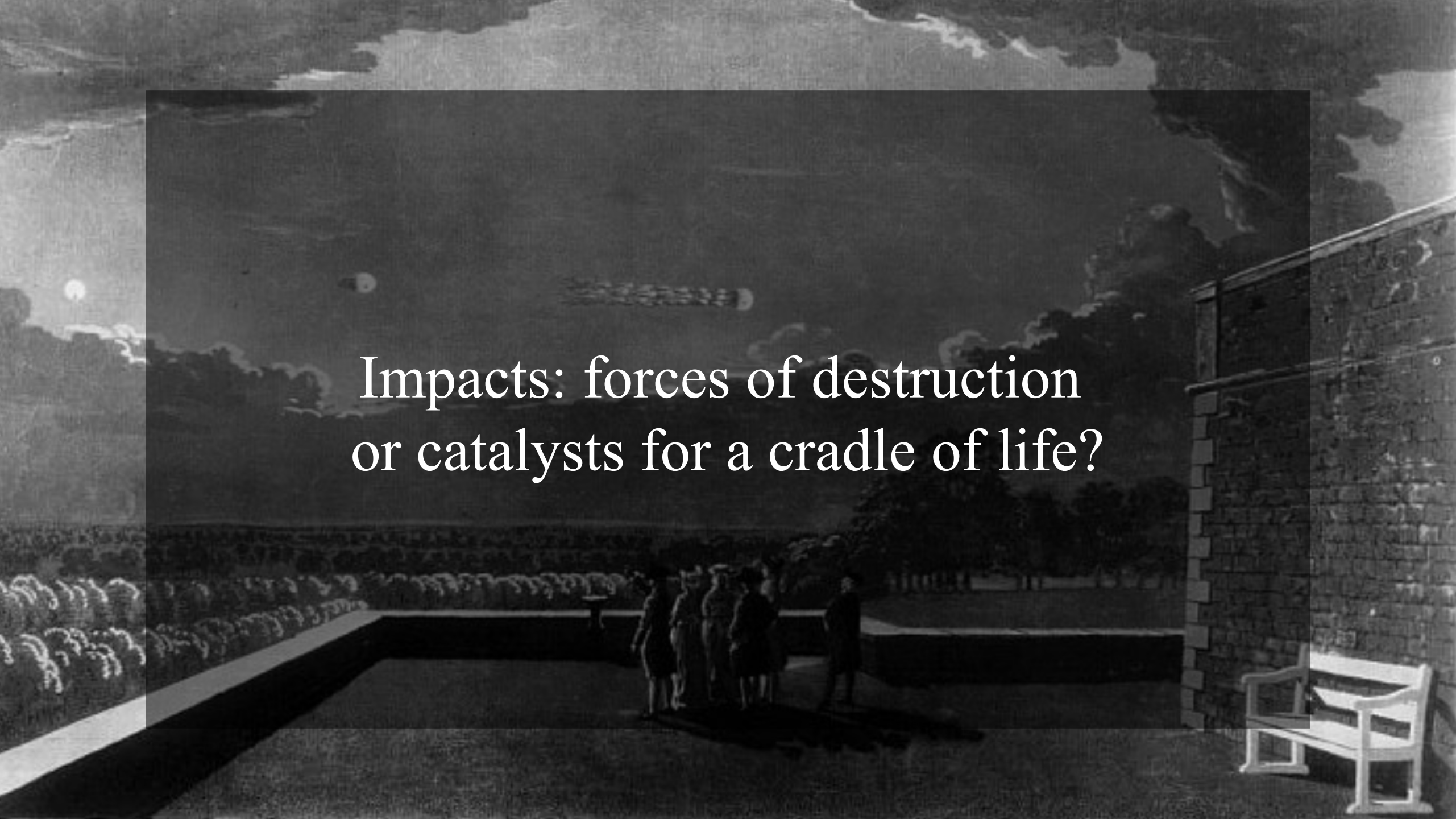

cooler, more oxidized,
more acid Hadean ocean
<30 °C, pH ca.5.5
the universal ancestor
(not free-living)
temperature-, redox-,
and pH-gradient
DNA era
RNP era
RNA era
prebiotic
chemistry
organic precursors
amino acids
sugars
bases
H+
P2O7 4−
CO2
Fe2+ >> Fe3+
Ni2+
FeS
NiS
CH3COSR
reduced
carbon
compounds
ocean
crust
HS−
H2CO
CH3SH
CN−
CH4
NH3
geochemistry
H2
CO
hot, reduced, alkaline
hydrothermal solution
ca.100°C, pH ca.10

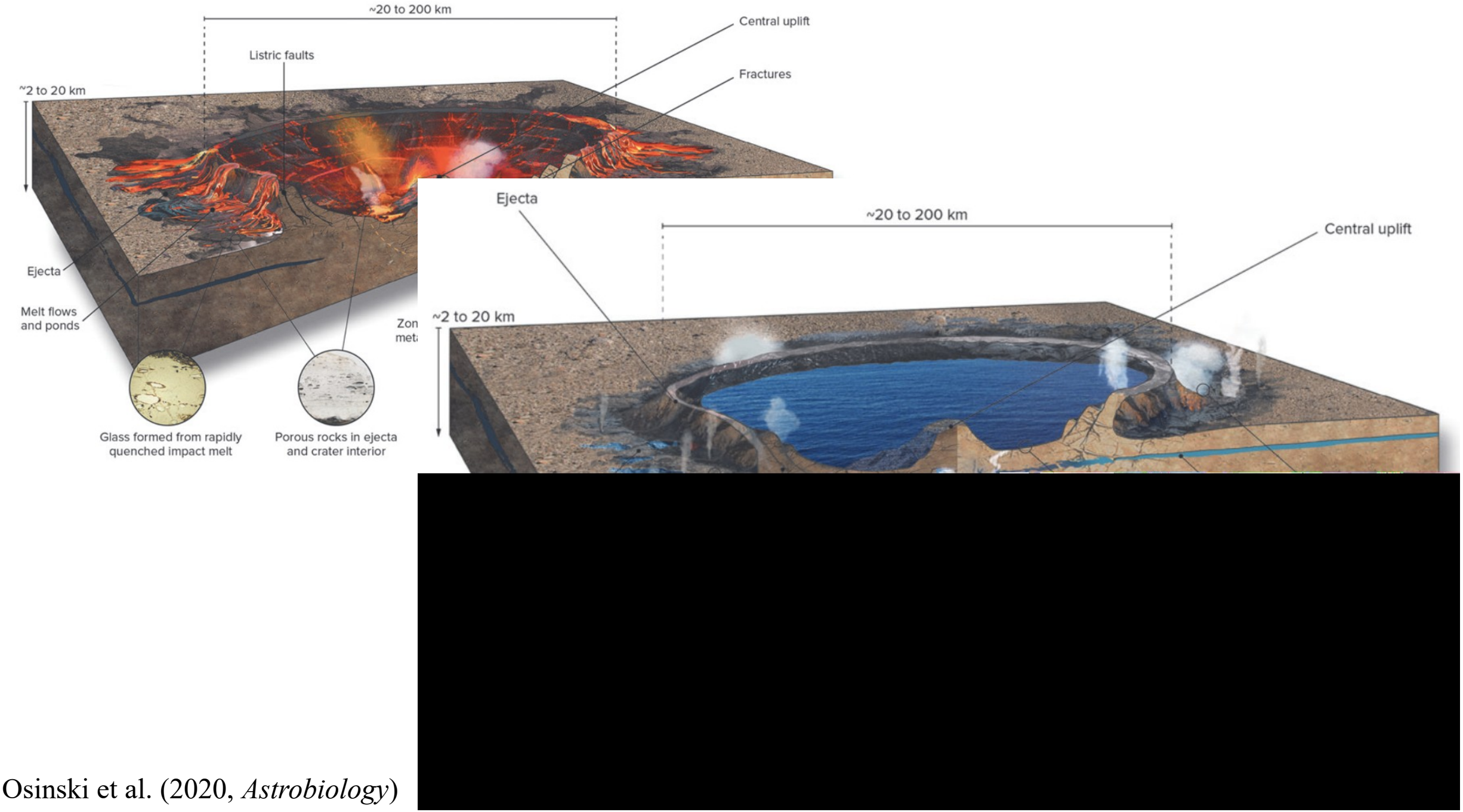


- Meteorites certainly delivered a rich diversity of organic materials to the early Earth that could have played a key role in prebiotic chemistry.

- Phosphate minerals associated with meteorite input (schreibersite) may have helped to overcome phosphate shortages on the early Earth by functioning as a phosphorylation agent (Pasek, 2017, *Geoscience Froniers*)

- It remains challenging, from a global palaeenvironmental perspective, to understand how meteoritic infall could have been concentrated in a way that raises its prebiotic plausibility above purely endogenous organic production.

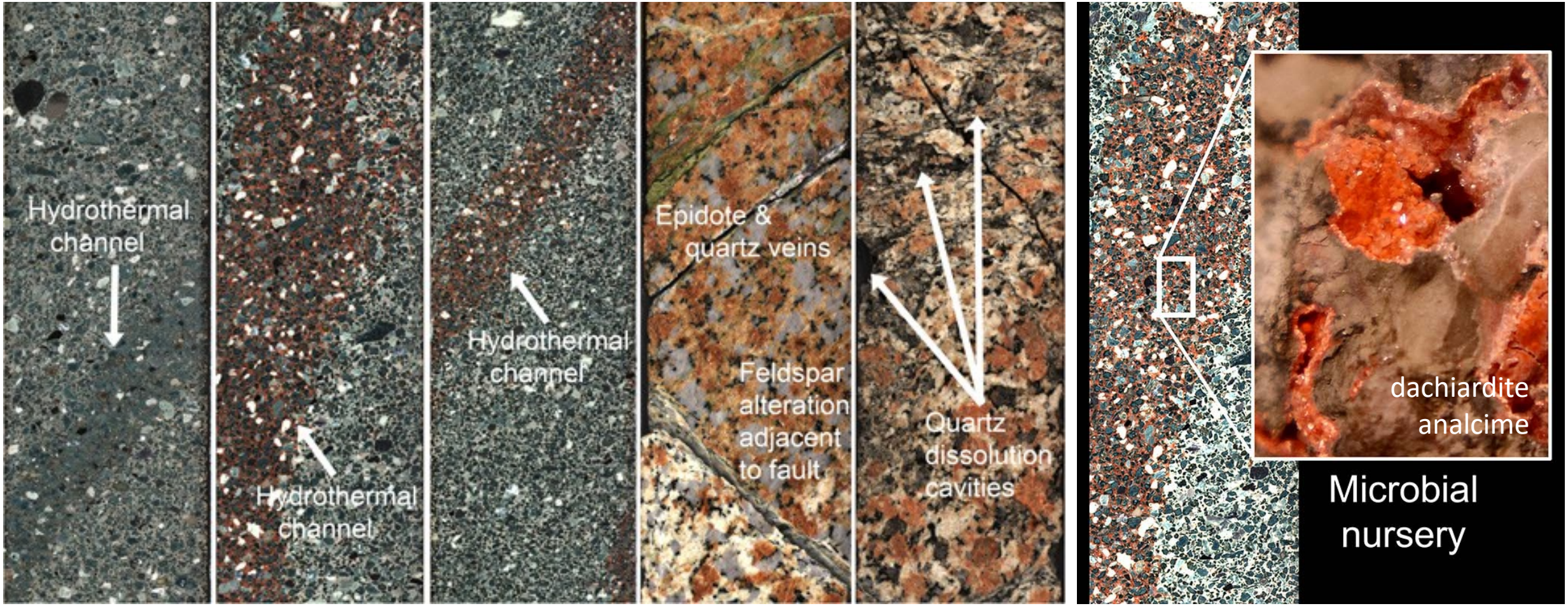

Impacts: forces of destruction
or catalysts for a cradle of life?



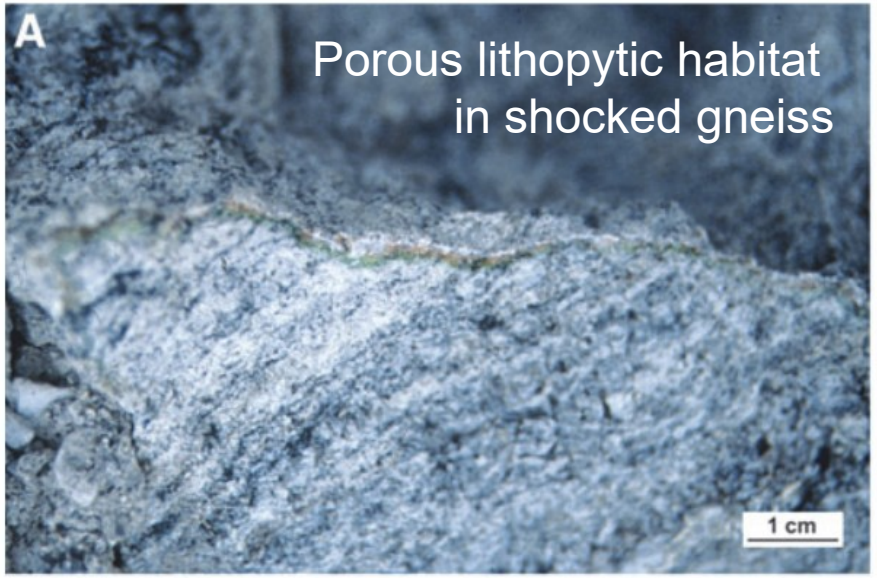
Osinski et al. (2020, *Astrobiology*)

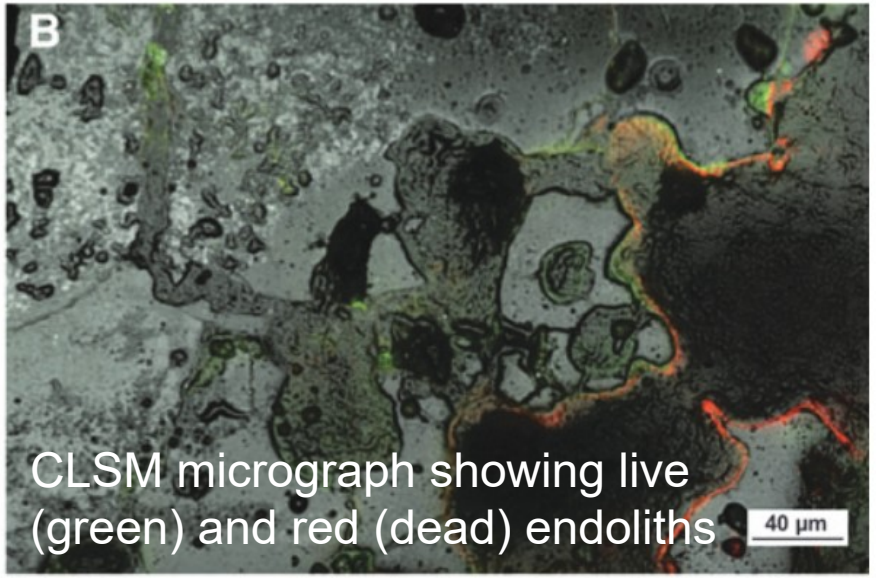
Chicxulub Impact Structure (Yucatán Peninsula, Mexico)

~200 km diameter
66 Ma (Oligocene), hydrothermal activity associated with SRB and potentially other chemotrophic pathways.



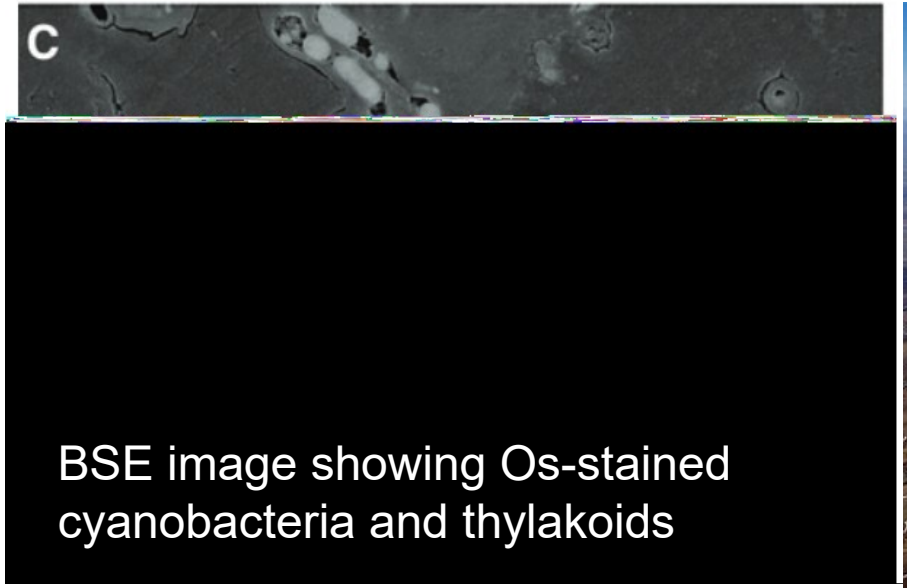
Kring (2000, GSA Today); Kring et al. (2020, *Science Advances*); Kring et al. (2021, *Astrobiology*)

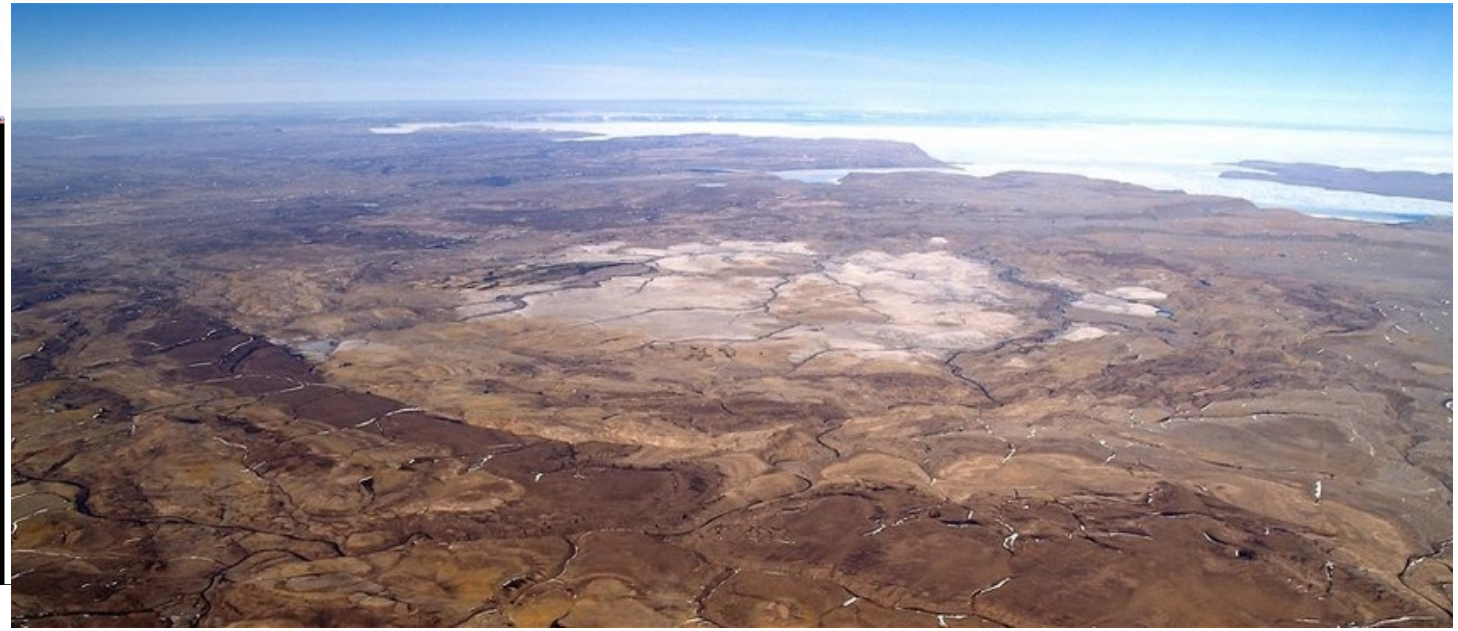




Haughton Impact Structure (Nunavut, Canada)

23 km diameter
31–32 Ma (Oligocene)

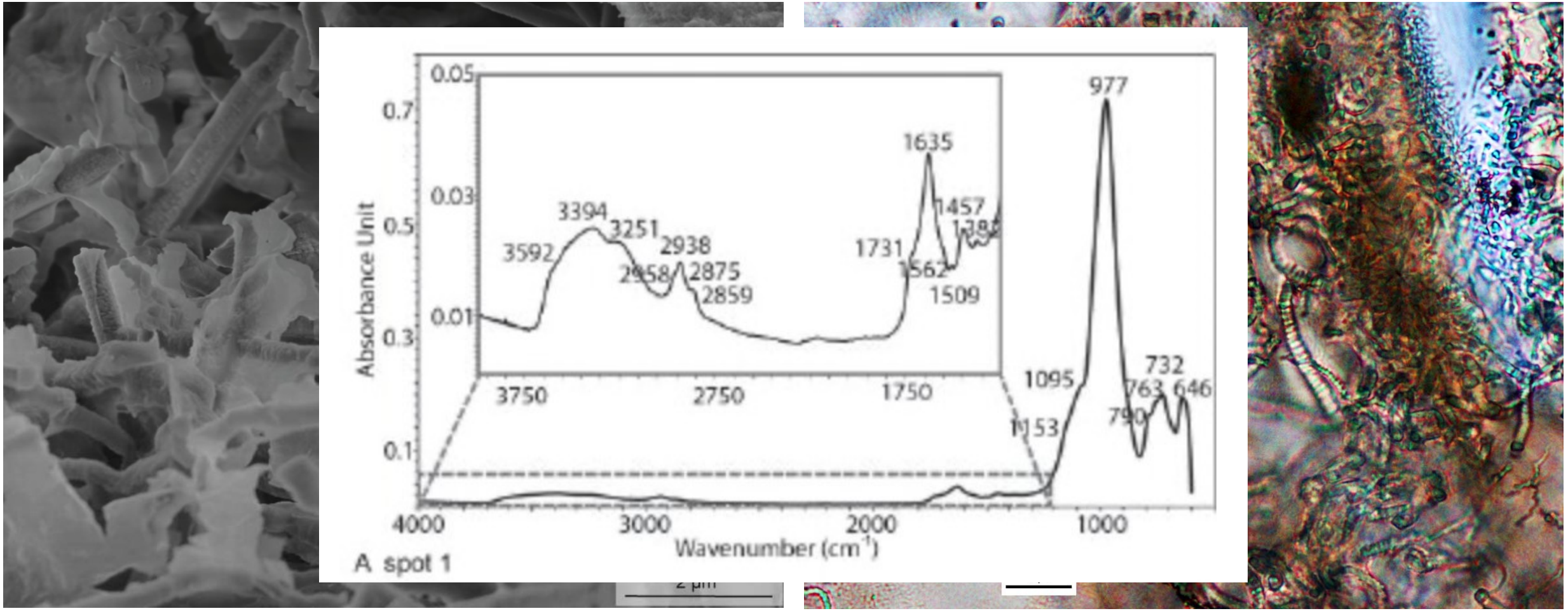




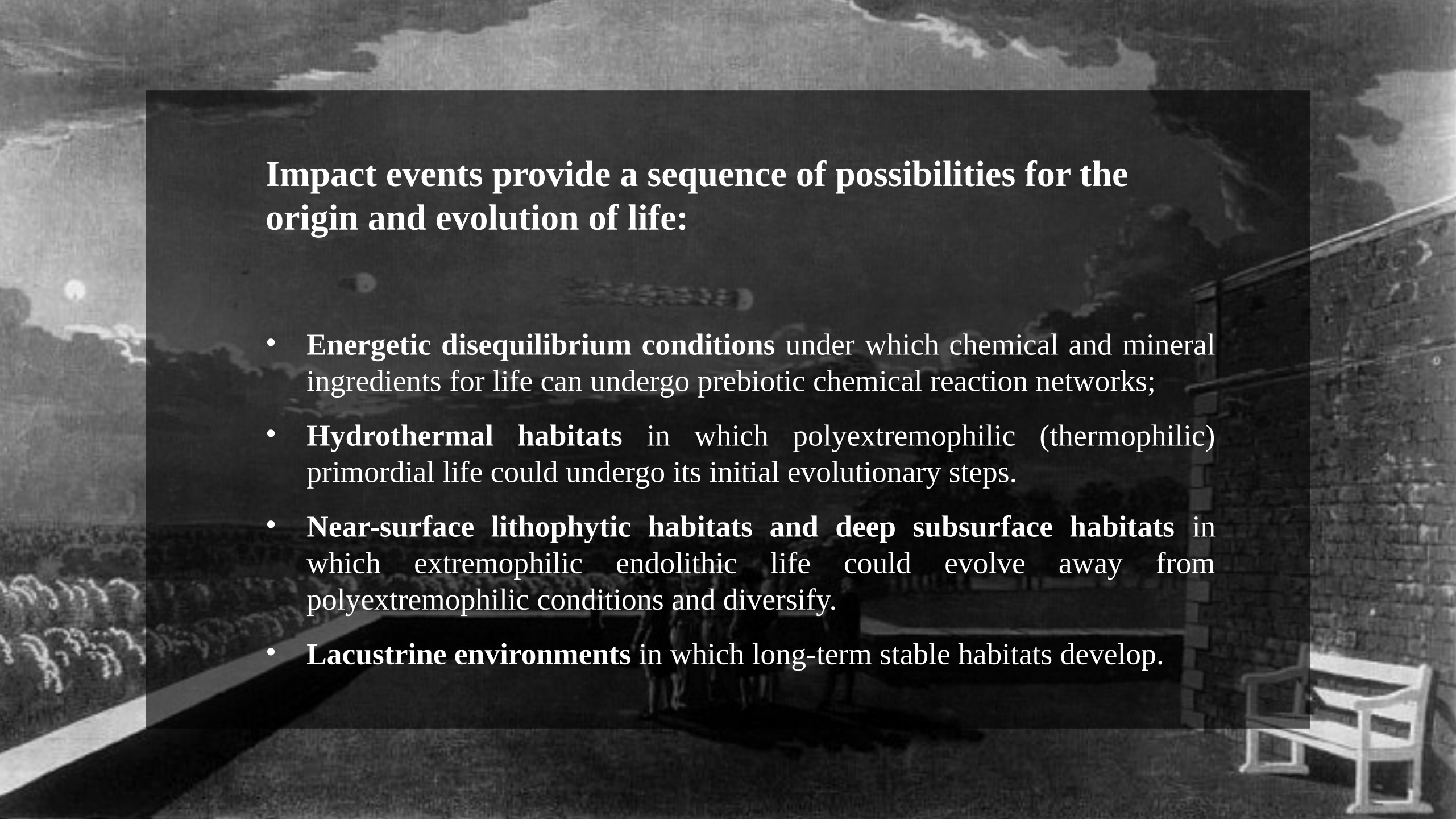
Pontefract et al. (2014, *Astrobiology*); Sapers et al. (2015, *EPSL*); Osinski et al. (2020, *Astrobiology*)

Nördlinger Ries impact structure

24 km diameter
14.8 Ma (Miocene)

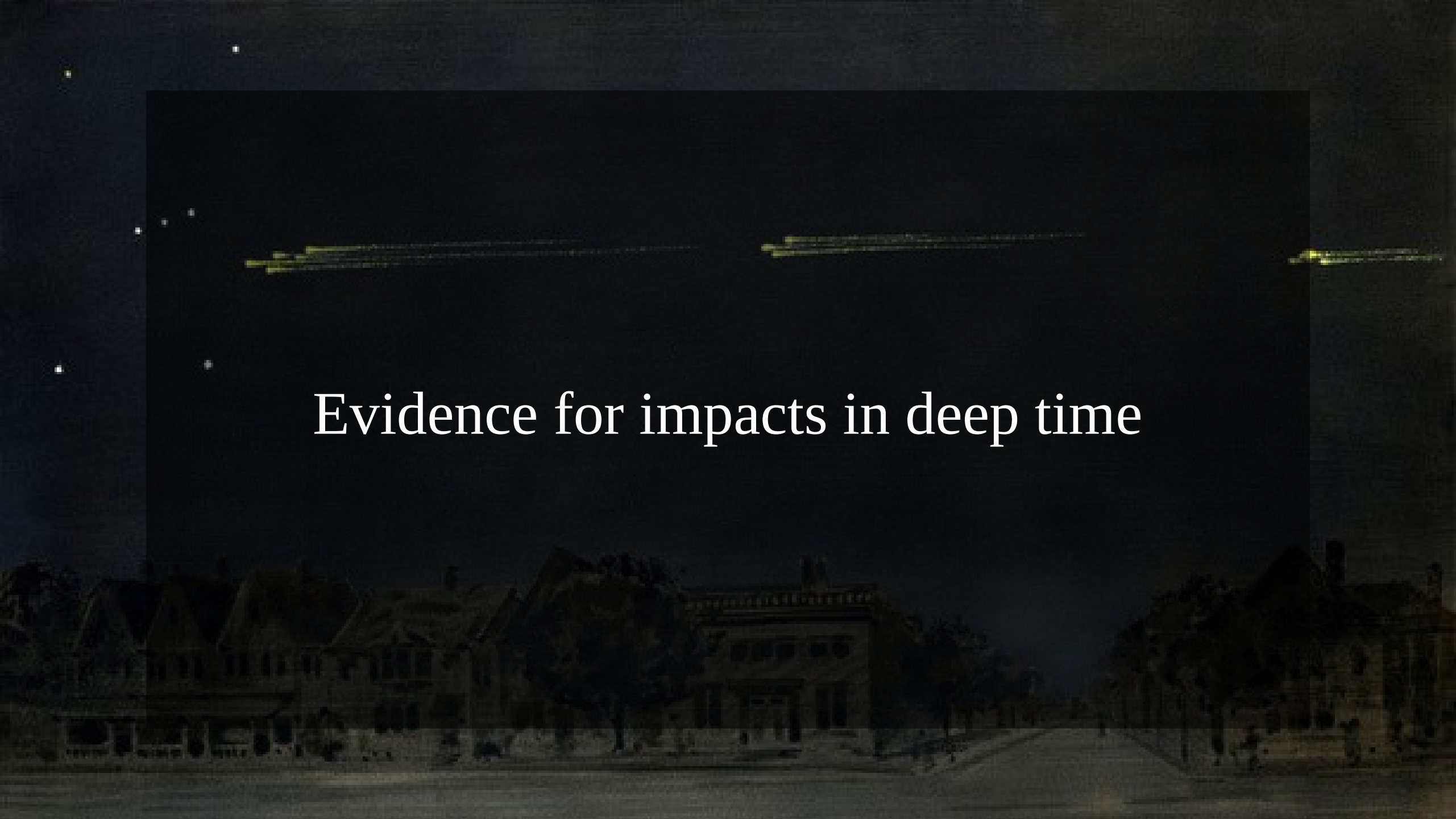


Sapers et al. (2014, *Geology*)



Impact events provide a sequence of possibilities for the origin and evolution of life:

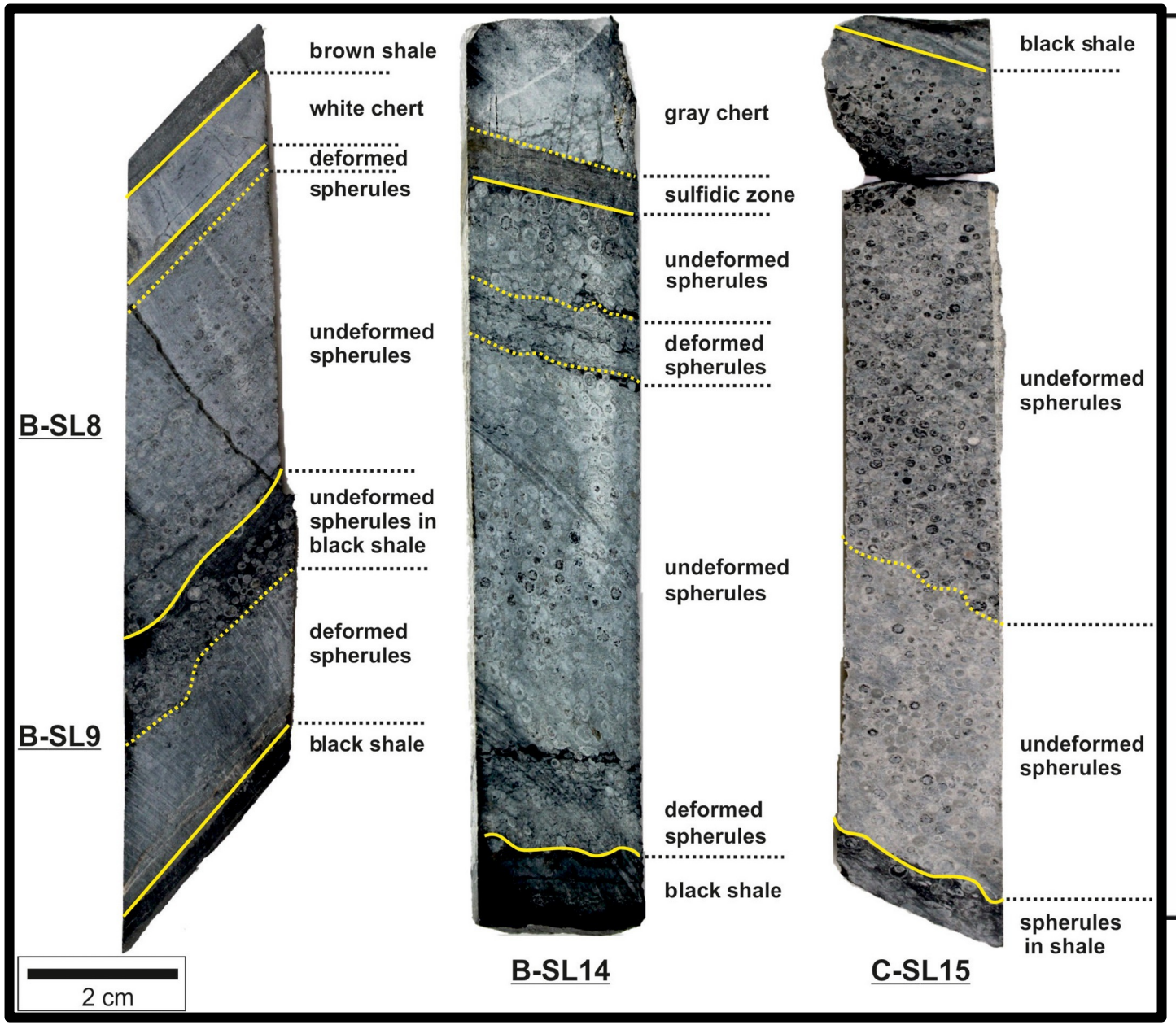
- **Energetic disequilibrium conditions** under which chemical and mineral ingredients for life can undergo prebiotic chemical reaction networks;
- **Hydrothermal habitats** in which polyextremophilic (thermophilic) primordial life could undergo its initial evolutionary steps.
- **Near-surface lithophytic habitats and deep subsurface habitats** in which extremophilic endolithic life could evolve away from polyextremophilic conditions and diversify.
- **Lacustrine environments** in which long-term stable habitats develop.

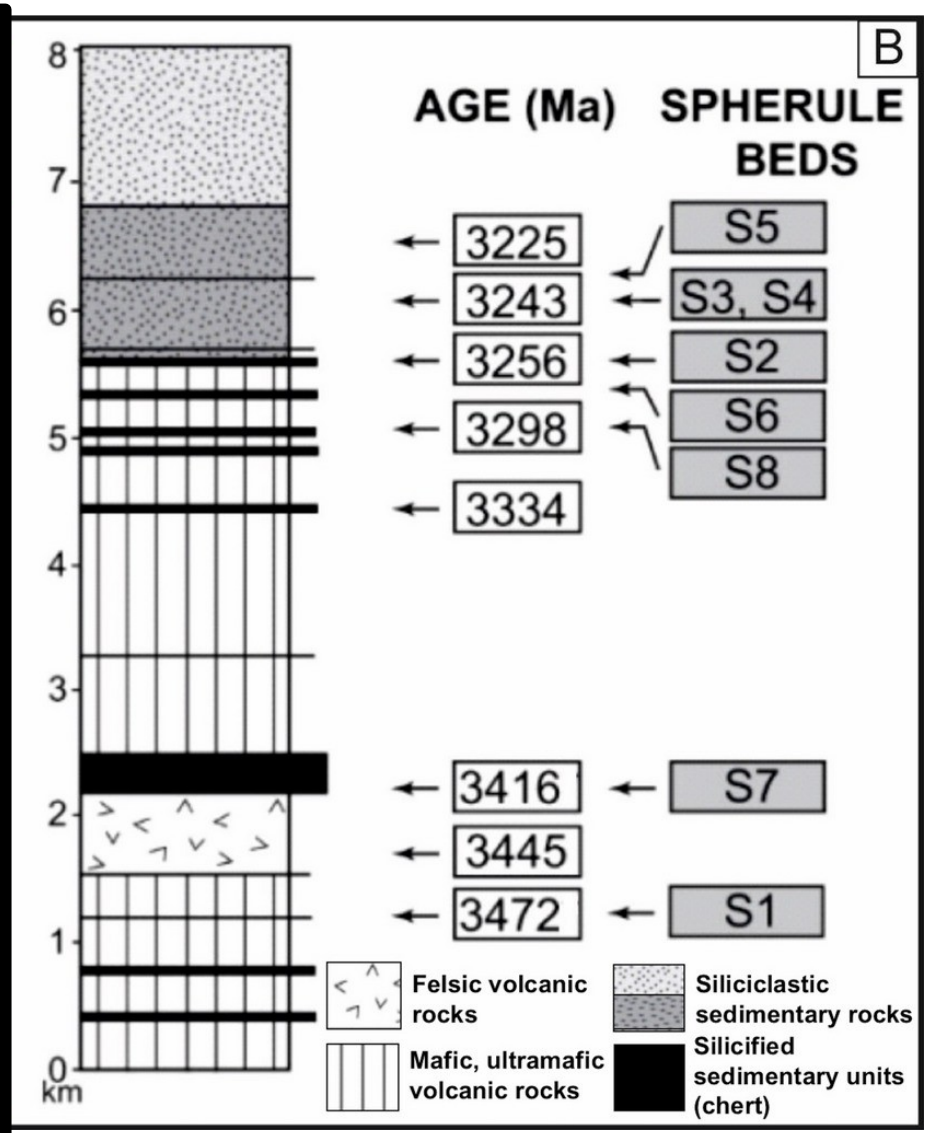


Evidence for impacts in deep time

Barberton greenstone belt, South Africa

Extraterrestrial spherule layers in the 3.2 Ga Fig Tree Group, Barberton?





Ozdemir et al. (2017, *MAPS*)

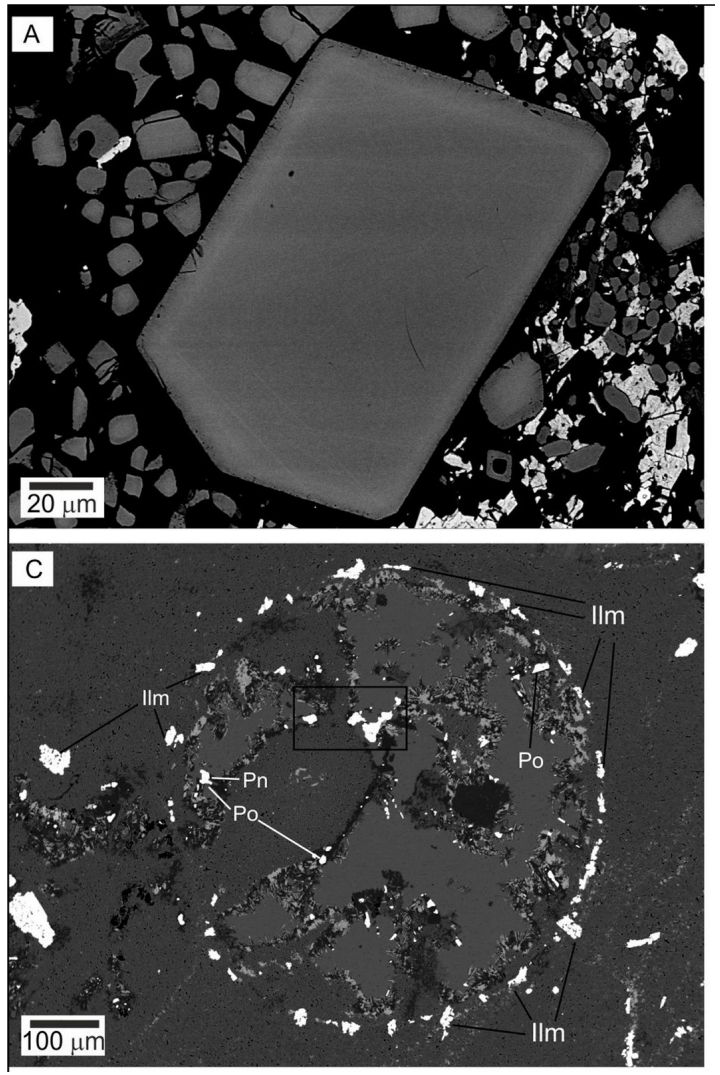
Extraterrestrial spherule layers in the 3.2 Ga Fig Tree Group, Barberton?

- Ni-Cr spinel of primary origin.
- Siderophile element contents of bulk samples show significant enrichments in Ni (up to 2 wt%) and Ir (up to ~3 ppm). Values are indicative of the presence of a meteoritic component.
- Lithophile and chalcophile element abundances indicate hydrothermal overprint.

Could this be an Archaean example of impact-induced hydrothermal activity, or simply hydrothermal overprint?

Absolute timing of hydrothermalism unclear. Also, hydrothermal activity in ancient contexts is common and possibly unremarkable.

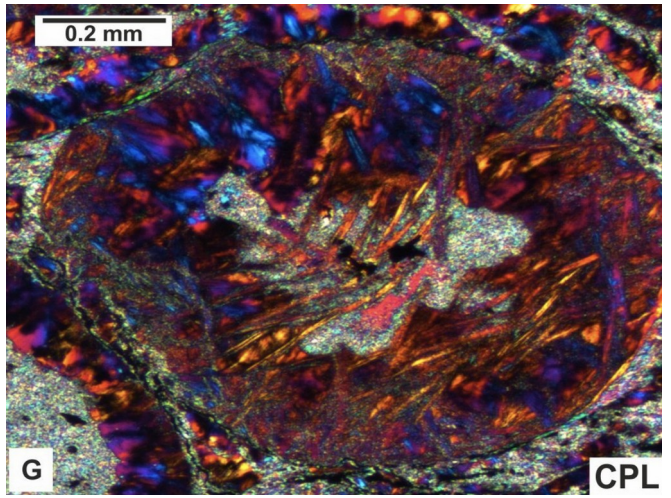
Difficulty of distinction from volcanic spherules.



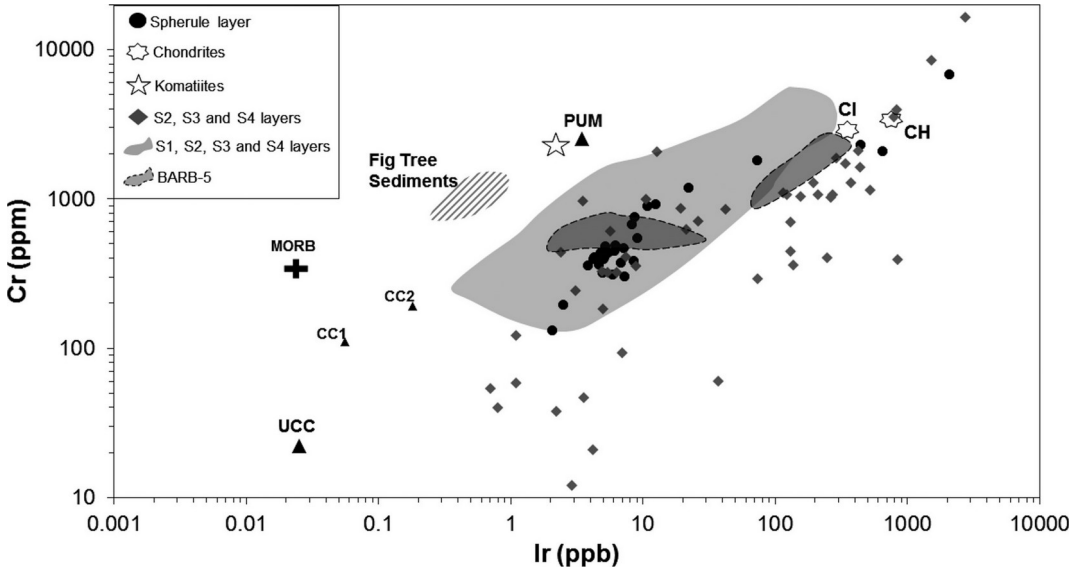
Ozdemir et al. (2017, *MAPS*)

Extraterrestrial spherule layers in the 3.2 Ga Fig Tree Group, Barberton?

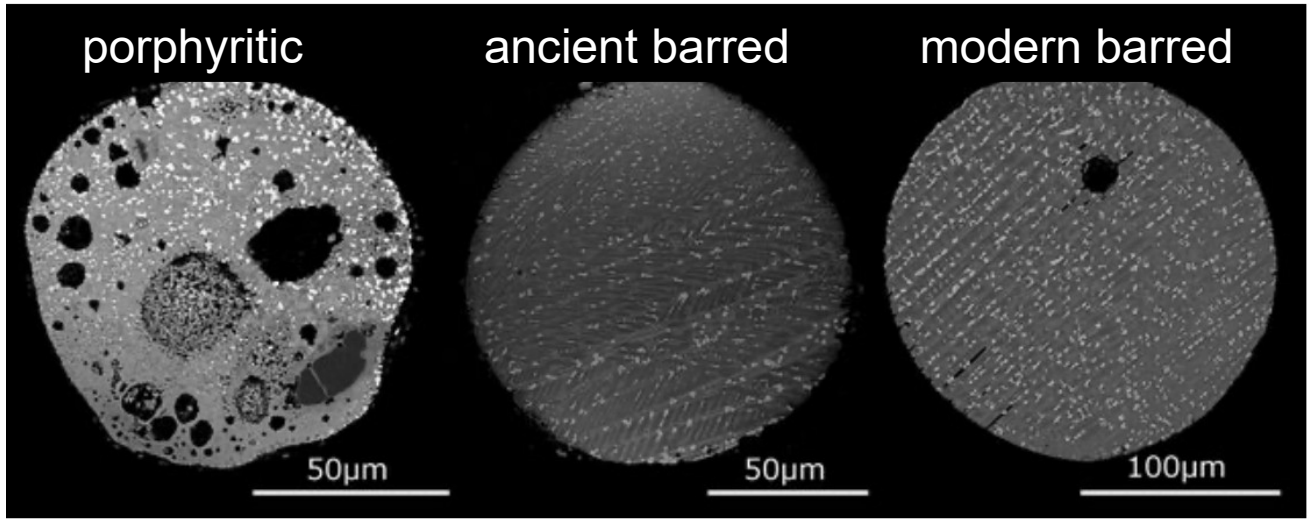
- Coupled evidence from petrographic observations and geochemical measurements.
  - Barred spherules similar to modern and ancient meteoritic spherules.
  - Ir–Cr compositions partially overlapping with chondritic values.
  - Possible, but not unambiguous – extraterrestrial origin.



Ozdemir et al. (2017, *MAPS*)



Ozdemir et al. (2017, *MAPS*)

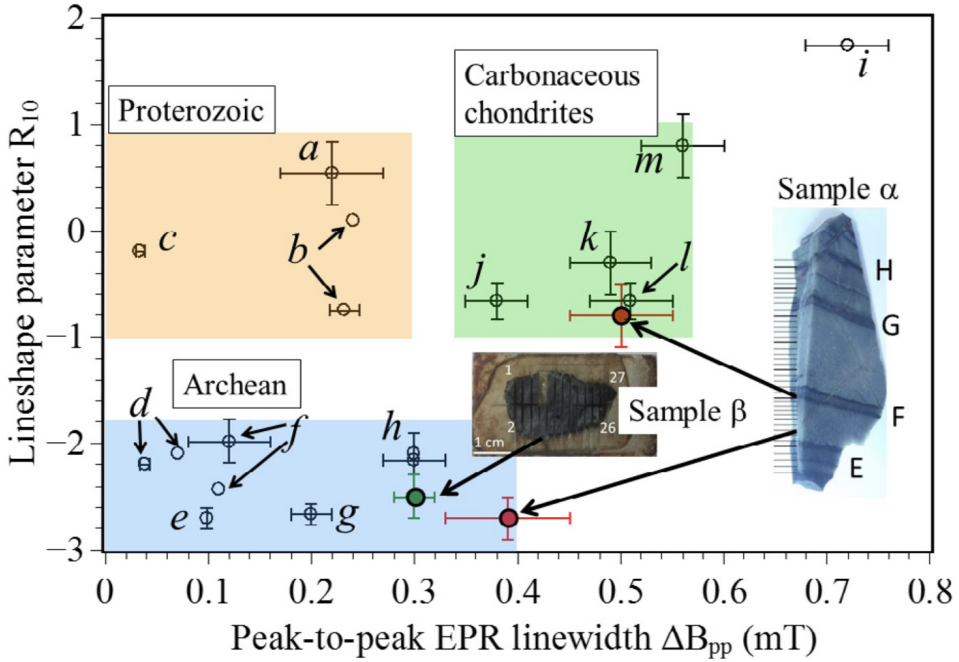


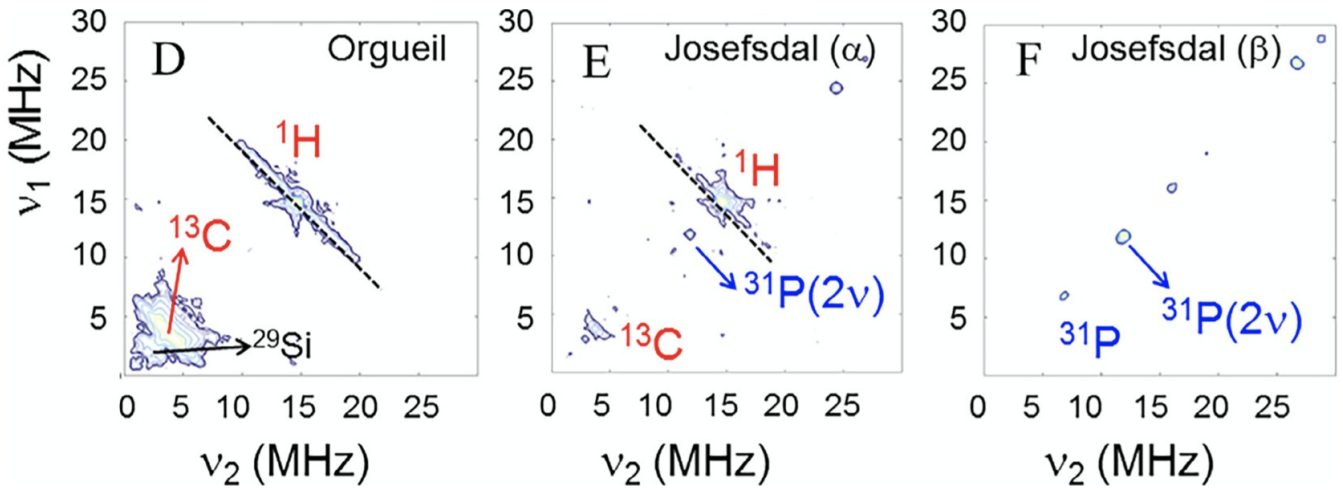
Suttle and Genge (2017, *EPSL*)

Extraterrestrial organic C-rich layers in the 3.33 Ga Onverwacht Group, Barberton?

- Continuous-wave-EPR and pulse-EPR reveals **insoluble organic matter** similar to the insoluble component of the hydrogenated organic matter in carbonaceous chondrites.
- Presence in only some layers of an **anomalous EPR signal attributed to Ni-Cr-Al ferrite spinel** nanoparticles, known to form during atmospheric entry of cosmic objects.
- Suggests that sedimentary horizons preserve organic materials of extraterrestrial origin.
- Hyperfine sublevel correlation pulse sequence (HYSCORE) was used to reveal interactions of the electron spin echoes of carbonaceous matter: similarity to extraterrestrial signals
- **Possible – but again not unambiguous – extraterrestrial origin.**

Gourier et al. (2019, *GCA*)





Ancient impact environments as tools for interpreting an impact-induced origin of life ?

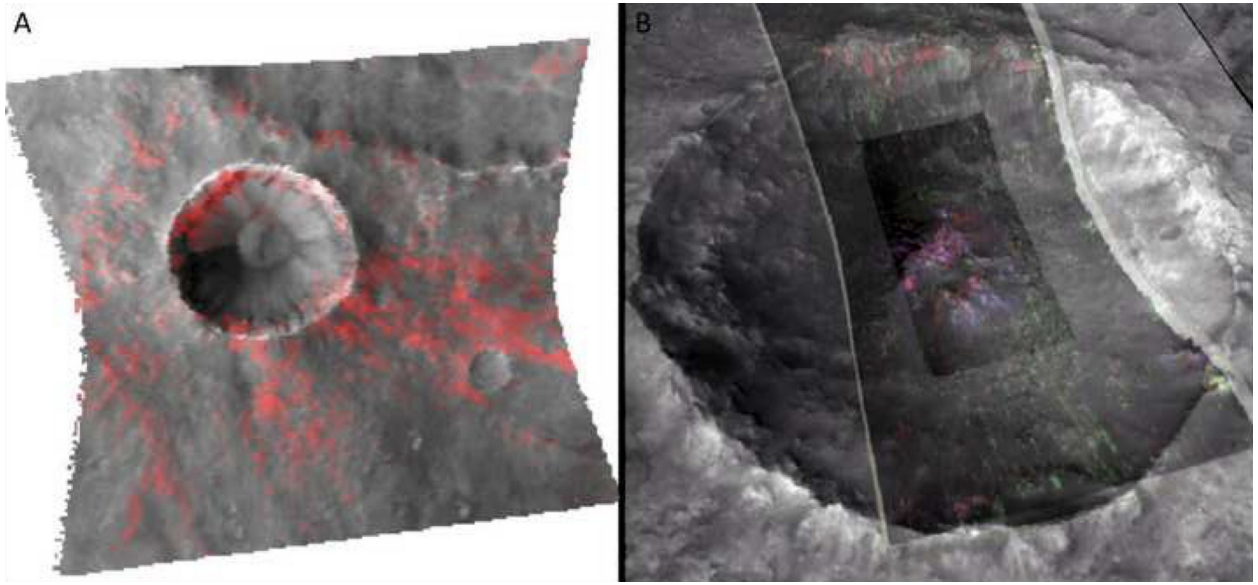
- Clear evidence in multiple localities for the importance of impacts throughout early Earth history.
- Well-studied examples are not explicitly linked to impact-induced hydrothermal systems.
- Preservation of organic materials and/or microbial fossils uncommon (however, this is hardly surprising for the early Earth).

Impact-induced hydrothermalism on Mars?

Unnamed ~22-km crater E of Toro Crater, Syrtis Major

CRISM spectra detect Fe-Mg- and Al-bearing phyllosilicates interpreted to arise from serpentinisation processes.

Distributed within the central uplift and walls (hydrothermally induced?) and within the ejecta blanket (ejected?)

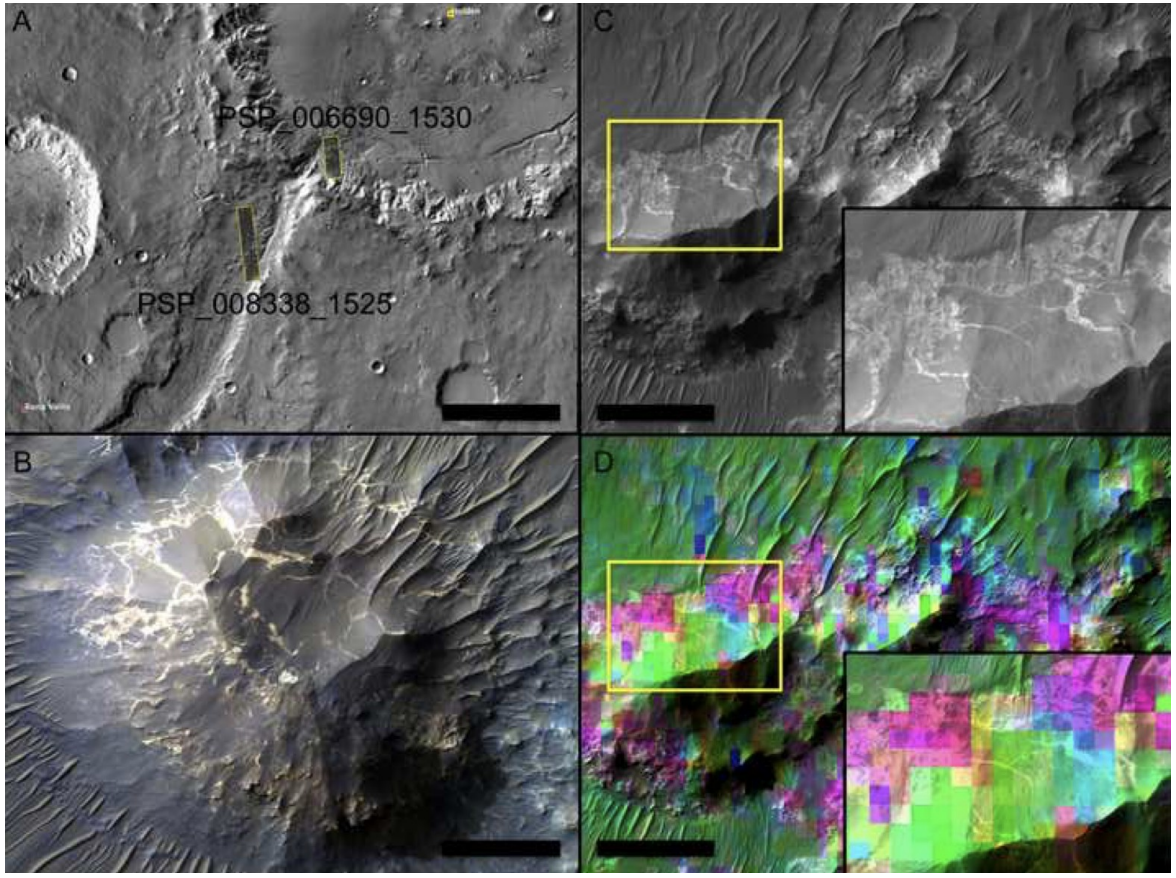


Marzo et al. (2010, *Icarus*)
Osinski et al. (2013; *Icarus*)
Turner et al. (2016, *JGR Planets*)

Holden impact crater exposed in Uzboi Valles, Mars

Correlation of light-toned fractures with CRISM spectral features indicating Fe-Mg phyllosilicates with bound water.

Potentially ascribed to Noachian/Hesperian impact-induced hydrothermal activity, but may also be diagenetic…



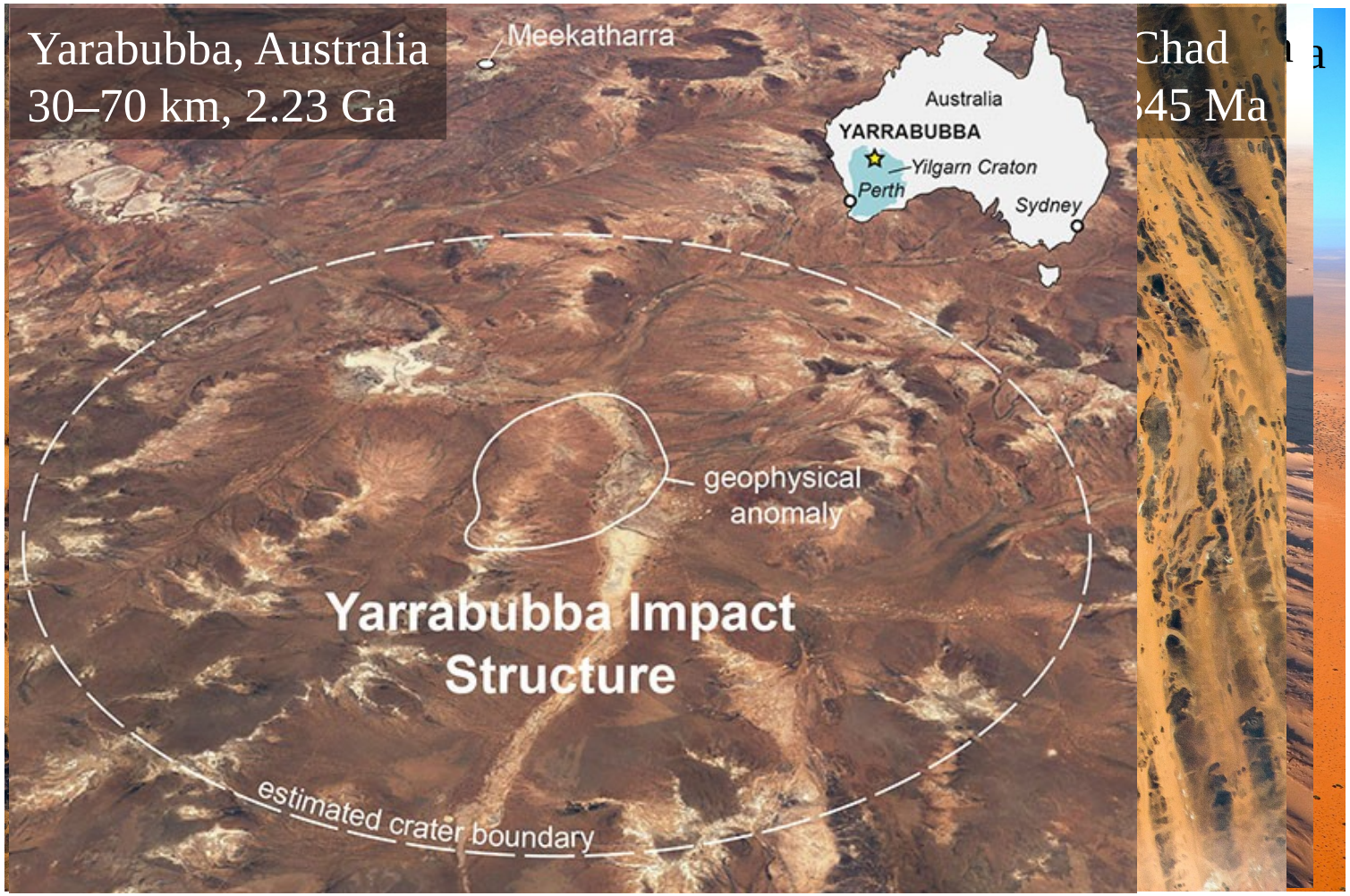

The next steps?

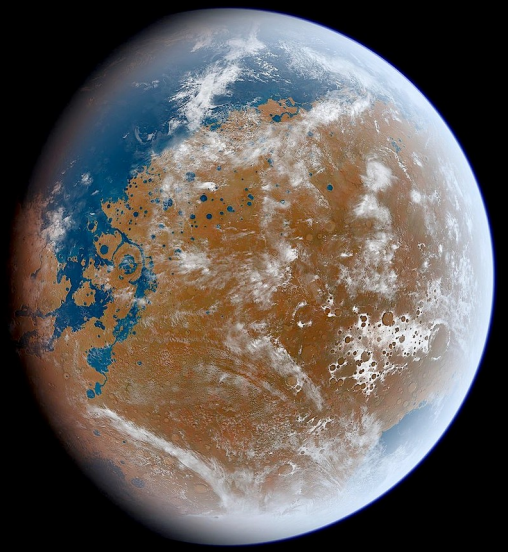
Where to search on Earth? Impact structures in low biomass regions?

- Impact craters in desertified regions, where the ambient biosphere is minimal in volume and diversity.
- Investigate changes in orgagic chemistry and the biosphere across crater-induced hydrothermal horizons.

Barringer Crater, USA
Negligible melt, negligible hydrothermalism
cf. Abramov and Kring (2007, MAPS)

"*Prebiotic chemistry in the wild*?"





Easier to investigate impact-induced prebiotic chemistry and biosphere on Mars?

- Punctuated habitability (*cf.* Westall et al., 2015) means that the ambient biosphere is effectively absent.
- Sampling inside and outside a crater-induced hydrothermal region would provide background and impact-induced materials.
- Not subject to ‘contamination’ from post-Noachian/Hesperian evolution of the biosphere.

Plausible roles for meteorites (and meteorite impacts) in the origin of life on Earth (and elsewhere)

Many possibilities, both on Earth and Mars.

Exogenous delivery and endogenous production?

Much field and analytical work remains to be done.