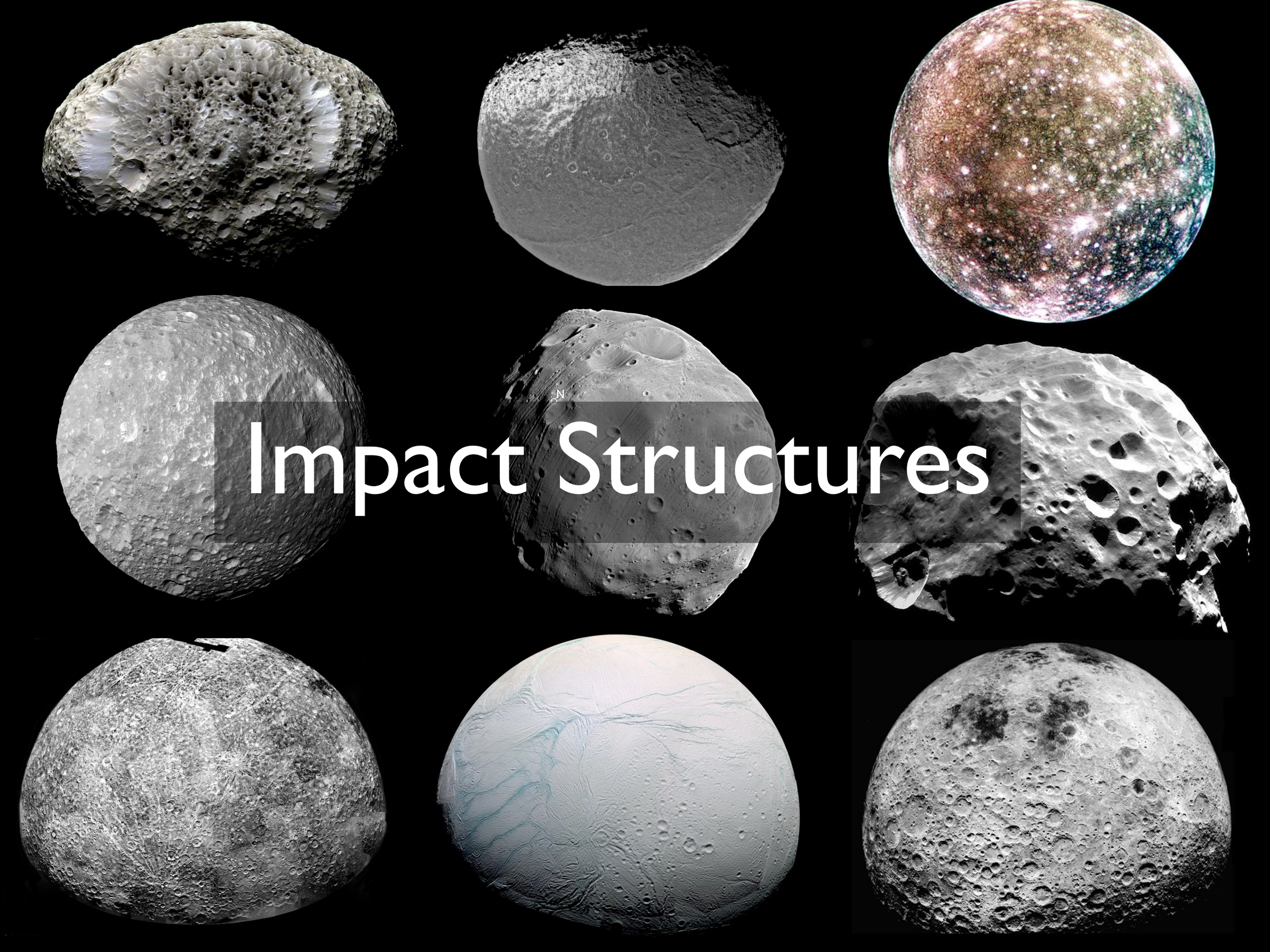
Impact-induced microbial habitats: implications for biosignature preservation in Nili Fossae

H. M. Sapers, A. Pontefract, G. R. Osinski, C. S. Cockell, K. Cannon, L. L. Tornabene, J. Mustard



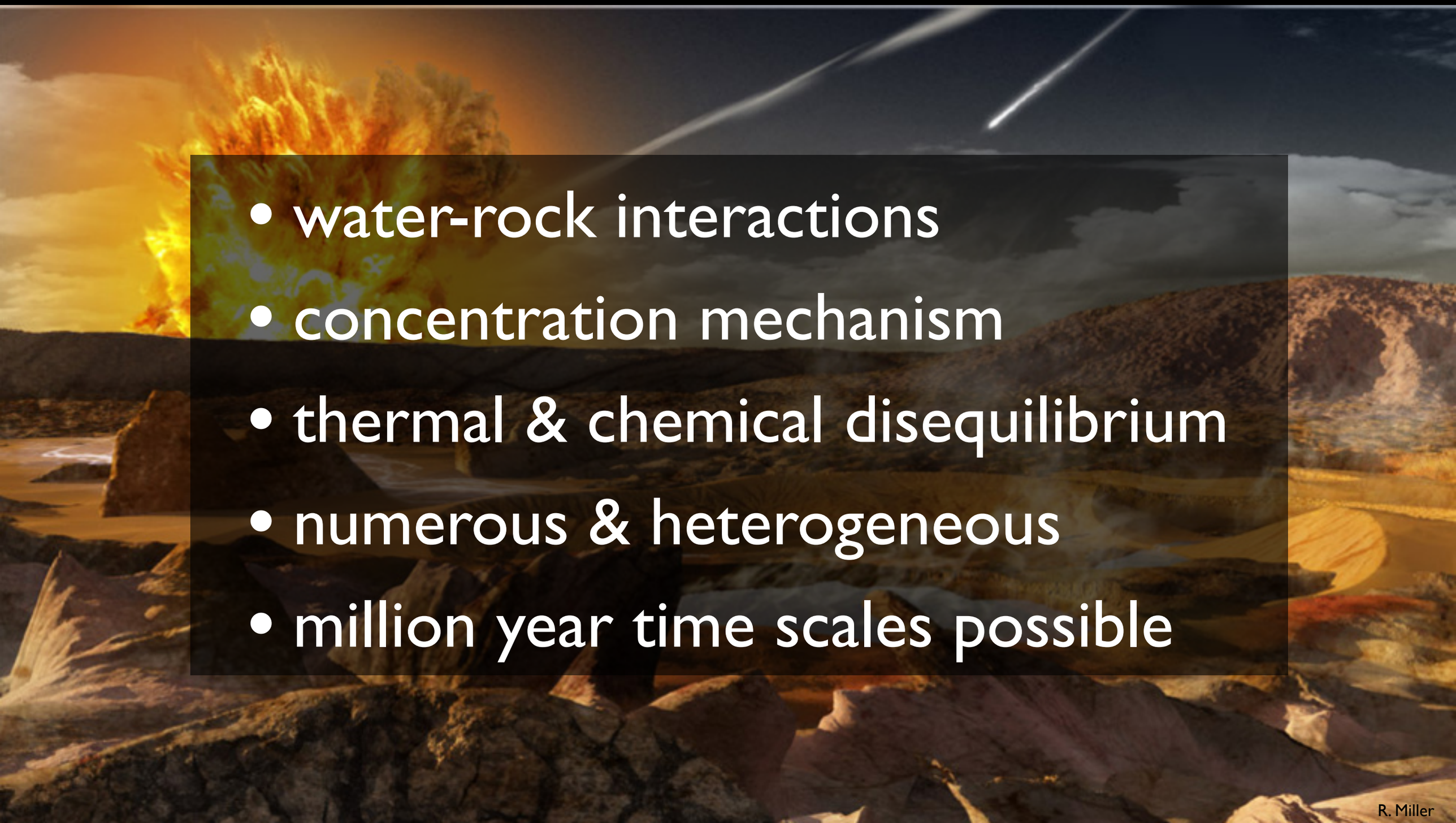
Impact Structures

Impact Structures

- dominant geological feature in the Solar System
- high impact flux on early Earth
- ubiquitous geological process
- exogenous heat/energy source
- unique impact products/substrates
- create mineralogical, chemical, physical interfaces
- delivery of organic molecules (e.g. amino acids, aromatics, organic acids, hydrocarbons...)
- delivery/release of volatiles (H_2O, H_2, CO_2)

Impact-generated Hydrothermal Systems

Impact-generated Hydrothermal Systems



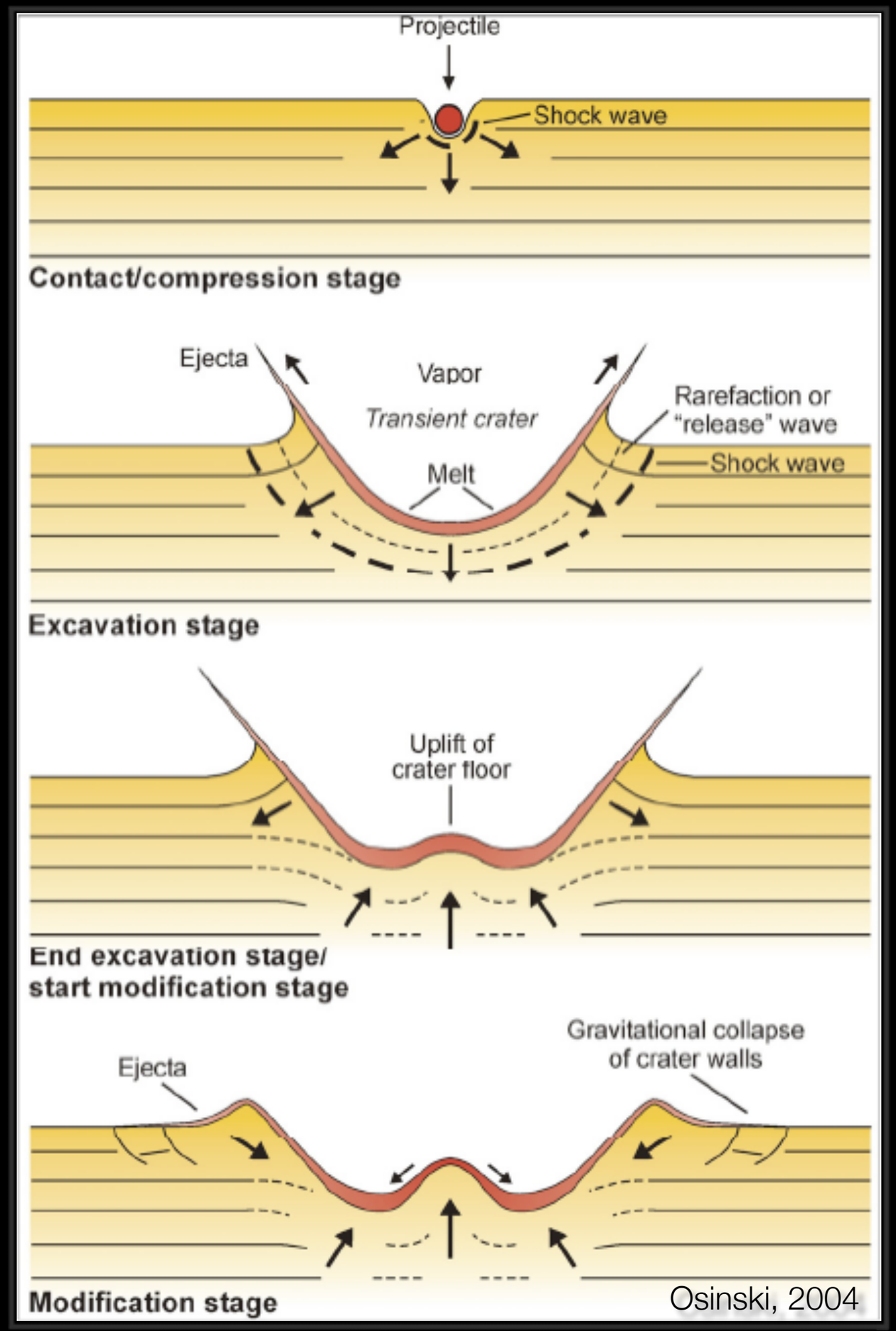
- water-rock interactions
- concentration mechanism
- thermal & chemical disequilibrium
- numerous & heterogeneous
- million year time scales possible

R. Miller

Crater formation

Three stages:

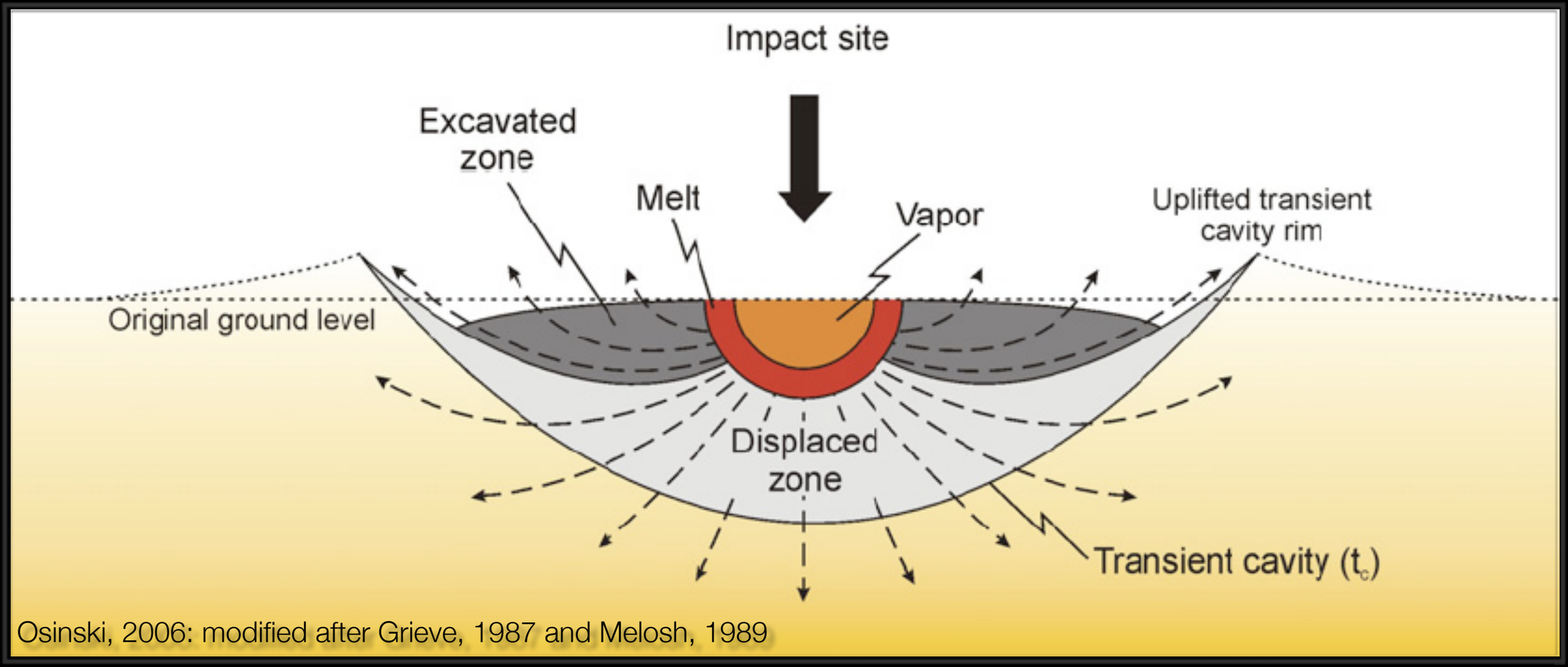
- Contact & compression
- Excavation
- Modification



Osinski, 2004

Crater formation

A 1 km diameter projectile can result in a 24 km diameter crater



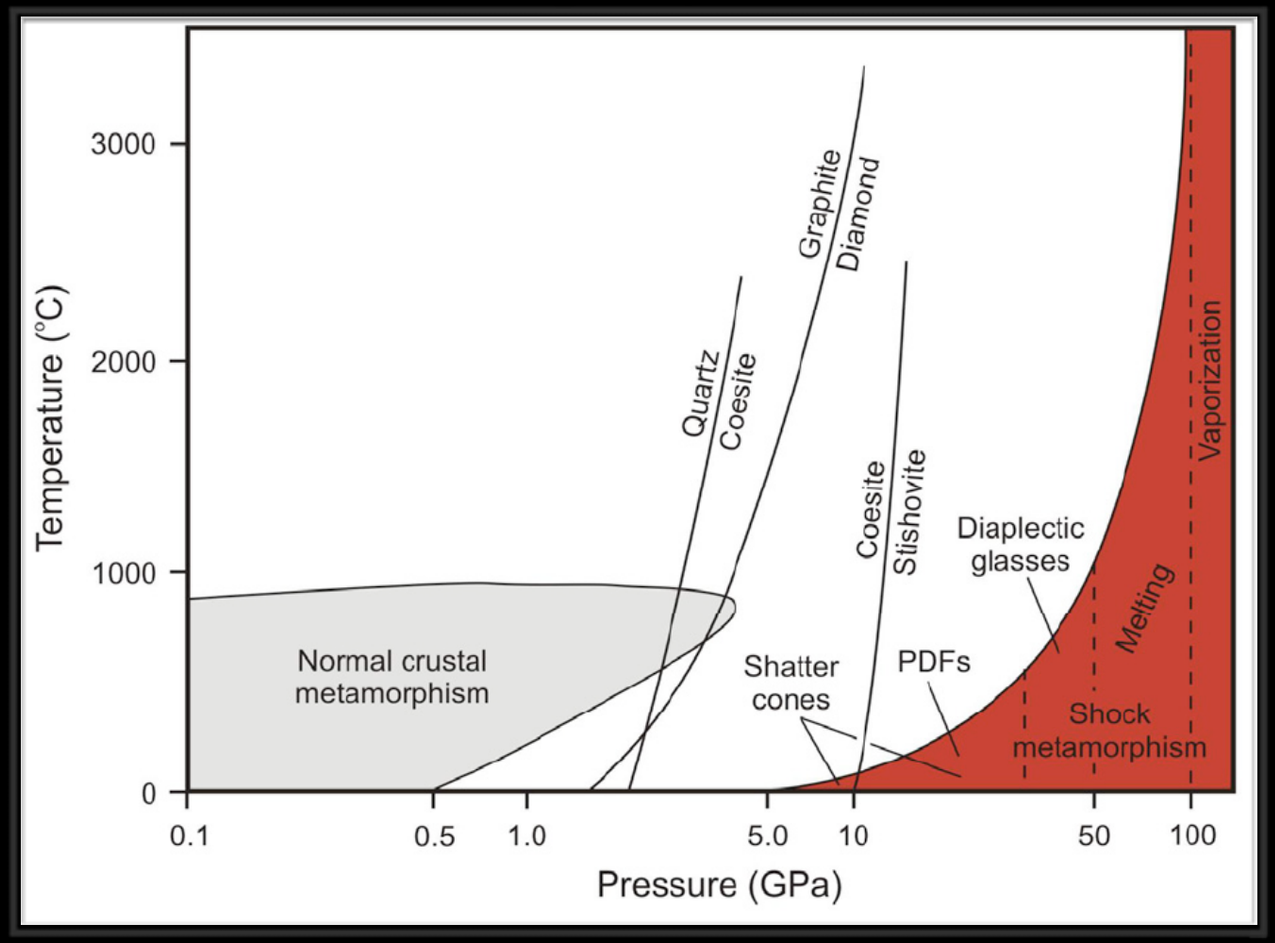
Osinski, 2006: modified after Grieve, 1987 and Melosh, 1989

projectile destroyed in craters > 1 km in diameter

Crater formation

Extreme physical parameters:

single point in time and space

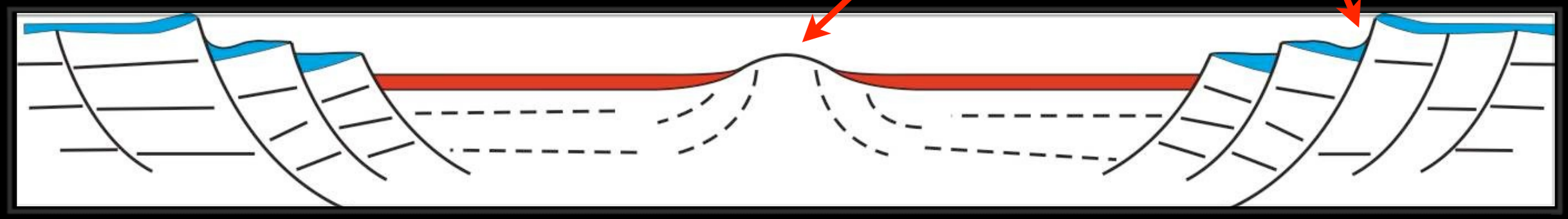


Osinski, 2006: modified from French, 1998

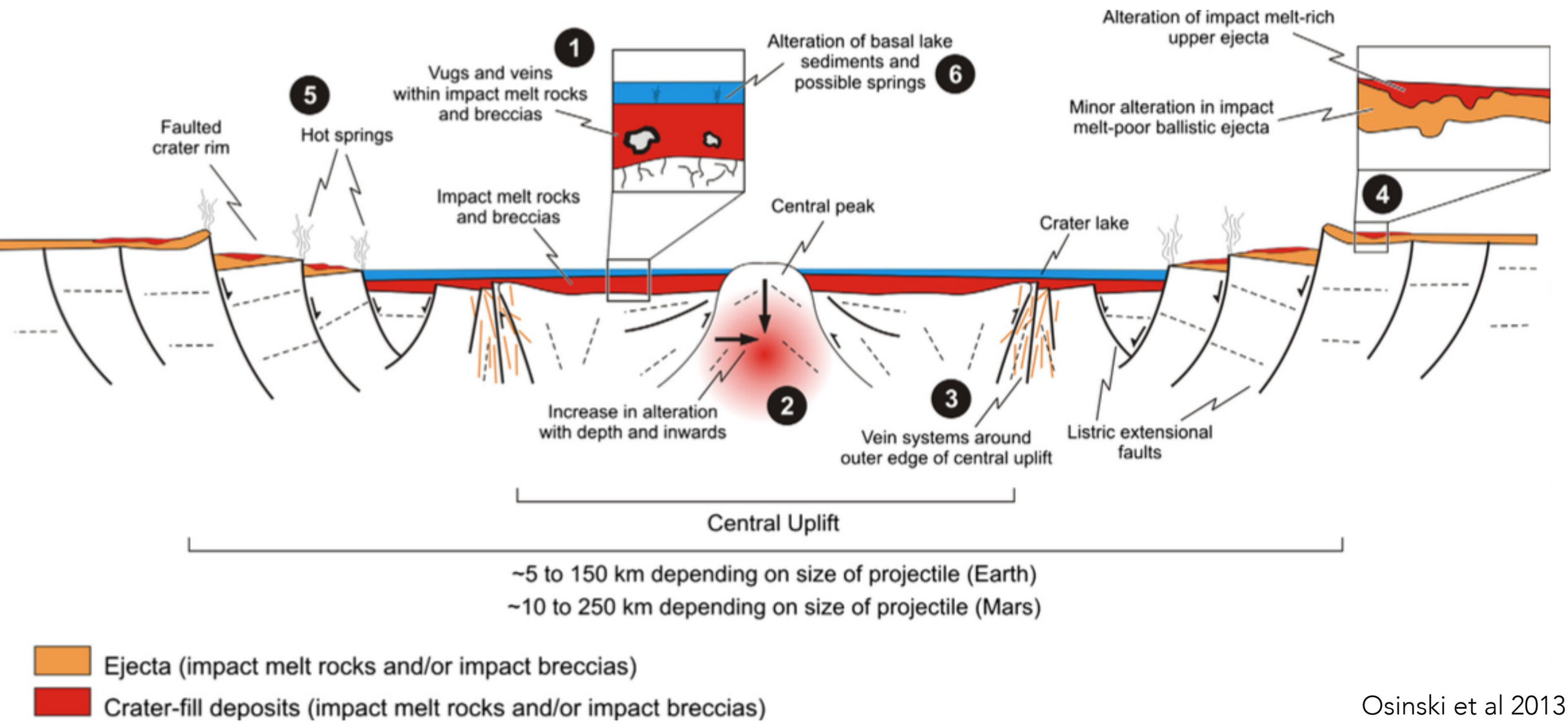
- modelled maximums
  - T=10 000^{0}C
  - P=400 GPa
- Large range in T and P

>100 GPa

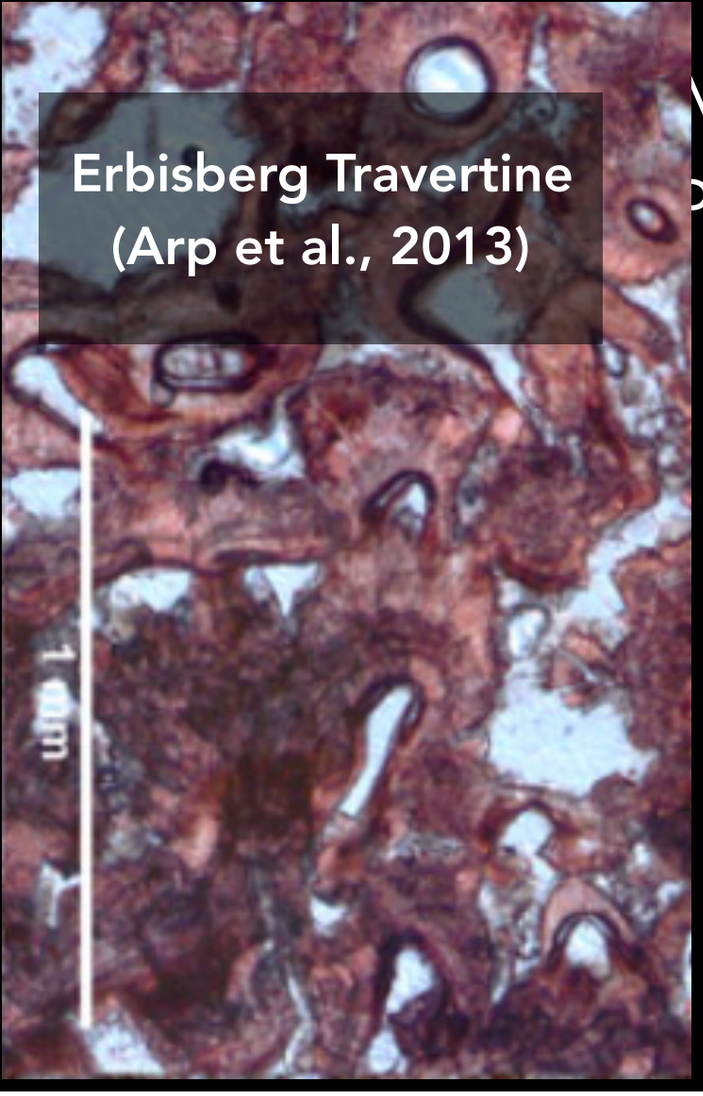
<2 GPa

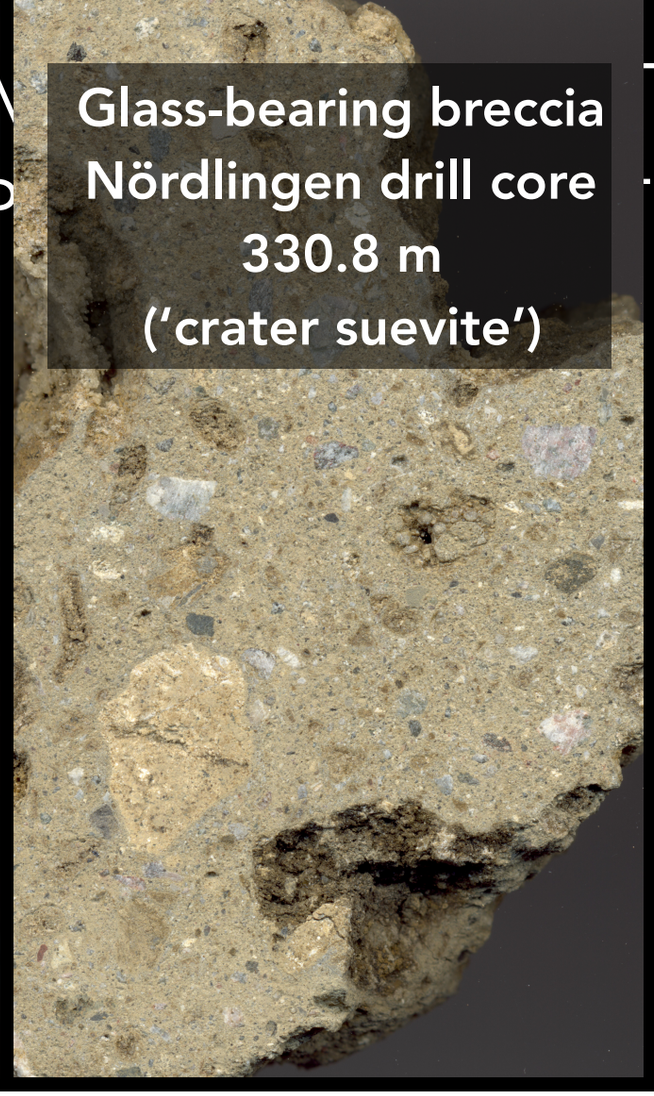


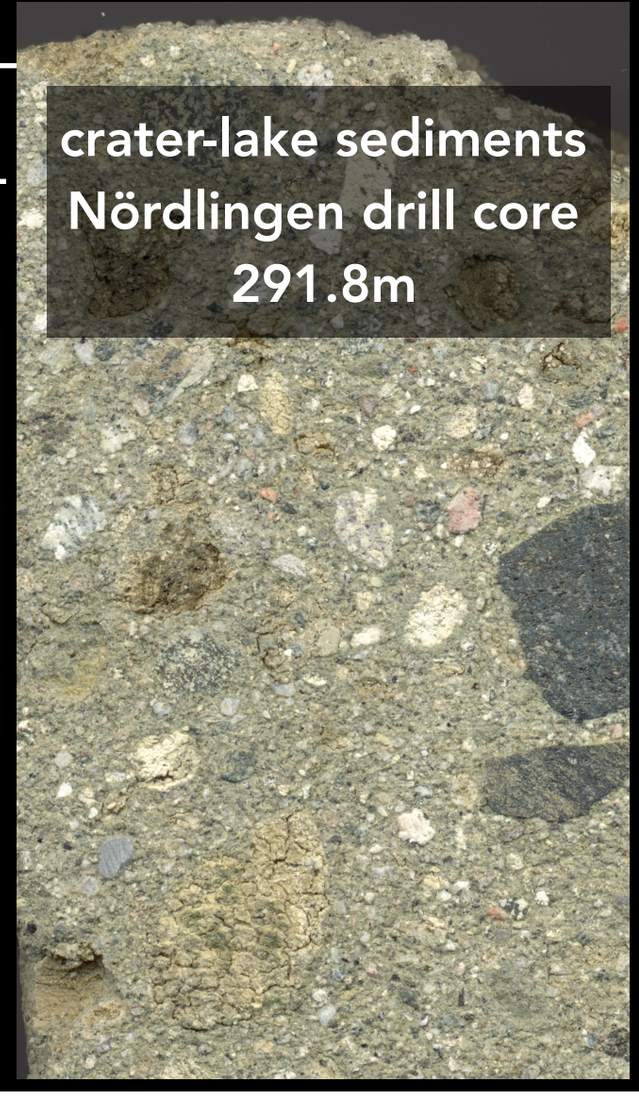
HYDROTHERMAL DEPOSITS IN 6 DISTINCT SETTINGS



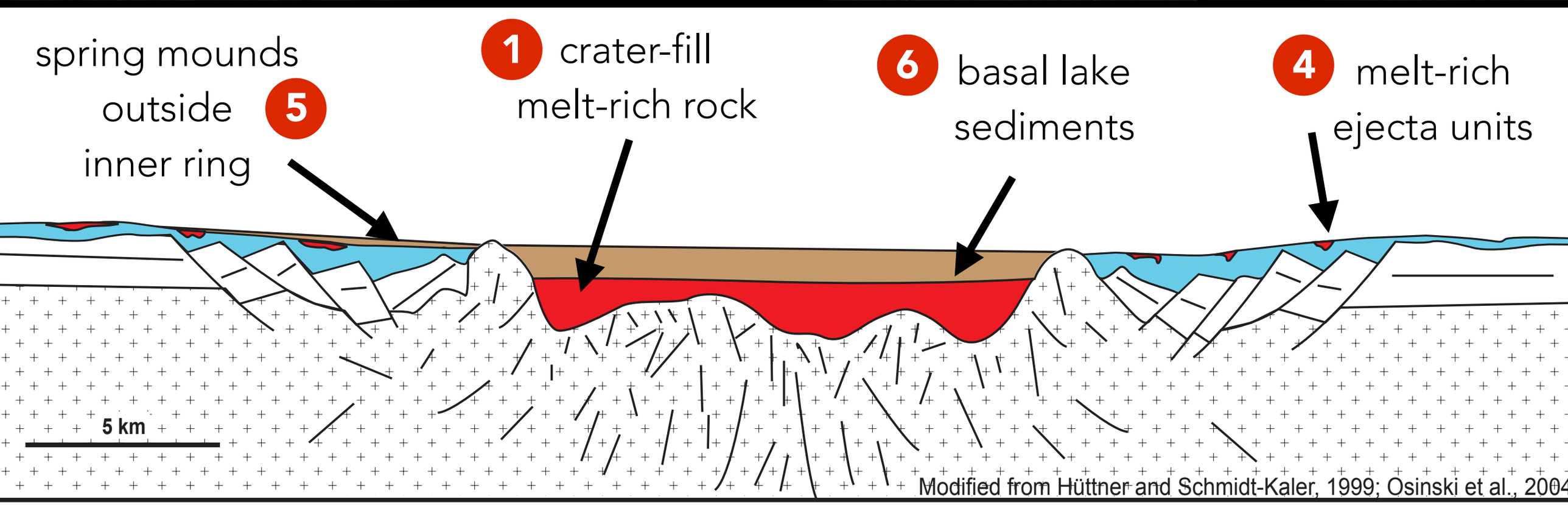
Osinski et al 2013


Erbisberg Travertine
(Arp et al., 2013)
1 mm


Glass-bearing breccia
Nördlingen drill core
330.8 m
('crater suevite')

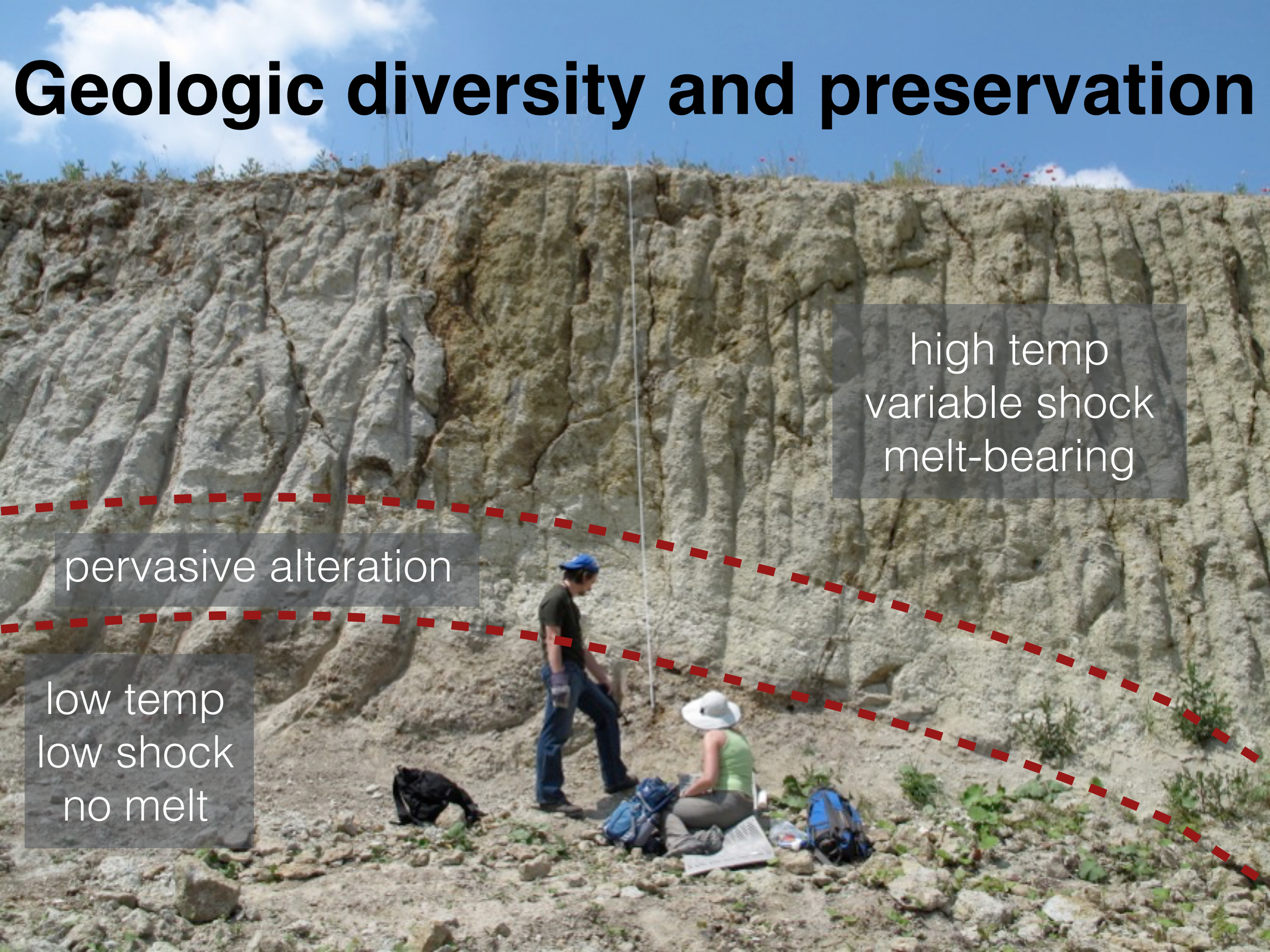

crater-lake sediments
Nördlingen drill core
291.8m

glass-bearing breccia
Aumühle quarry
('surficial suevite')

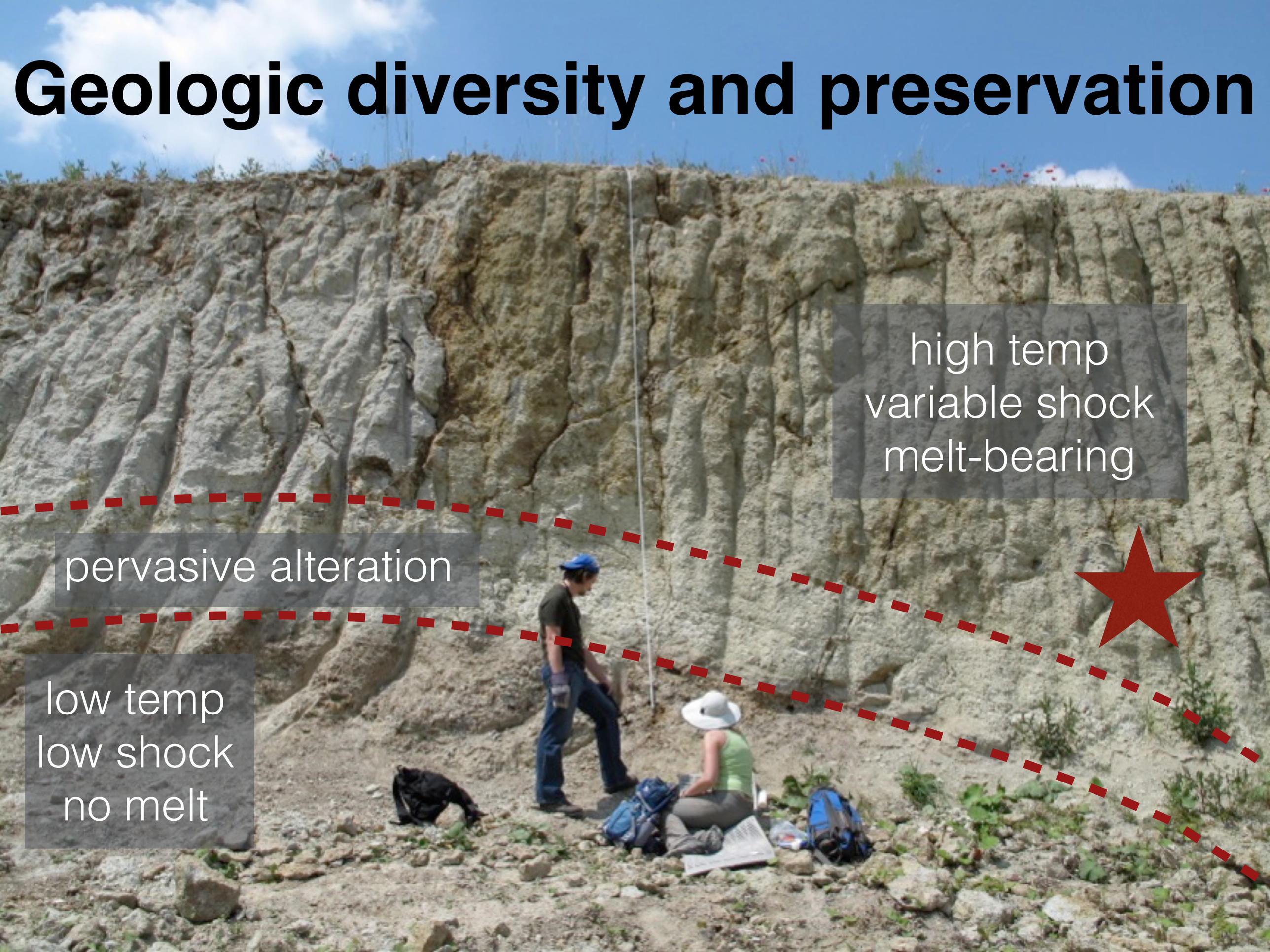

spring mounds
outside
inner ring
5
1
crater-fill
melt-rich rock
6
basal lake
sediments
4
melt-rich
ejecta units
5 km
Modified from Hüttner and Schmidt-Kaler, 1999; Osinski et al., 2004

Geologic diversity and preservation

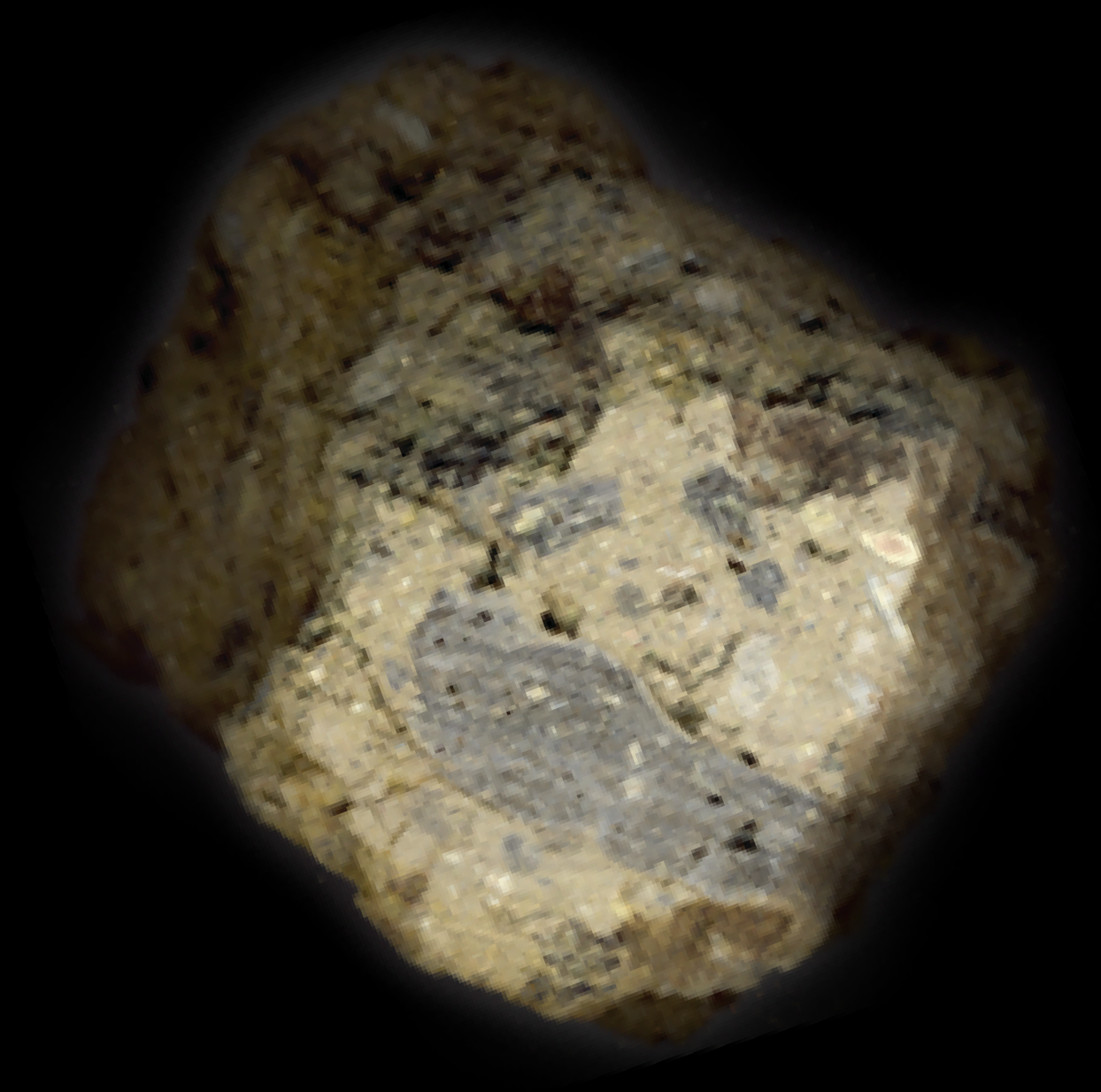
Geologic diversity and preservation



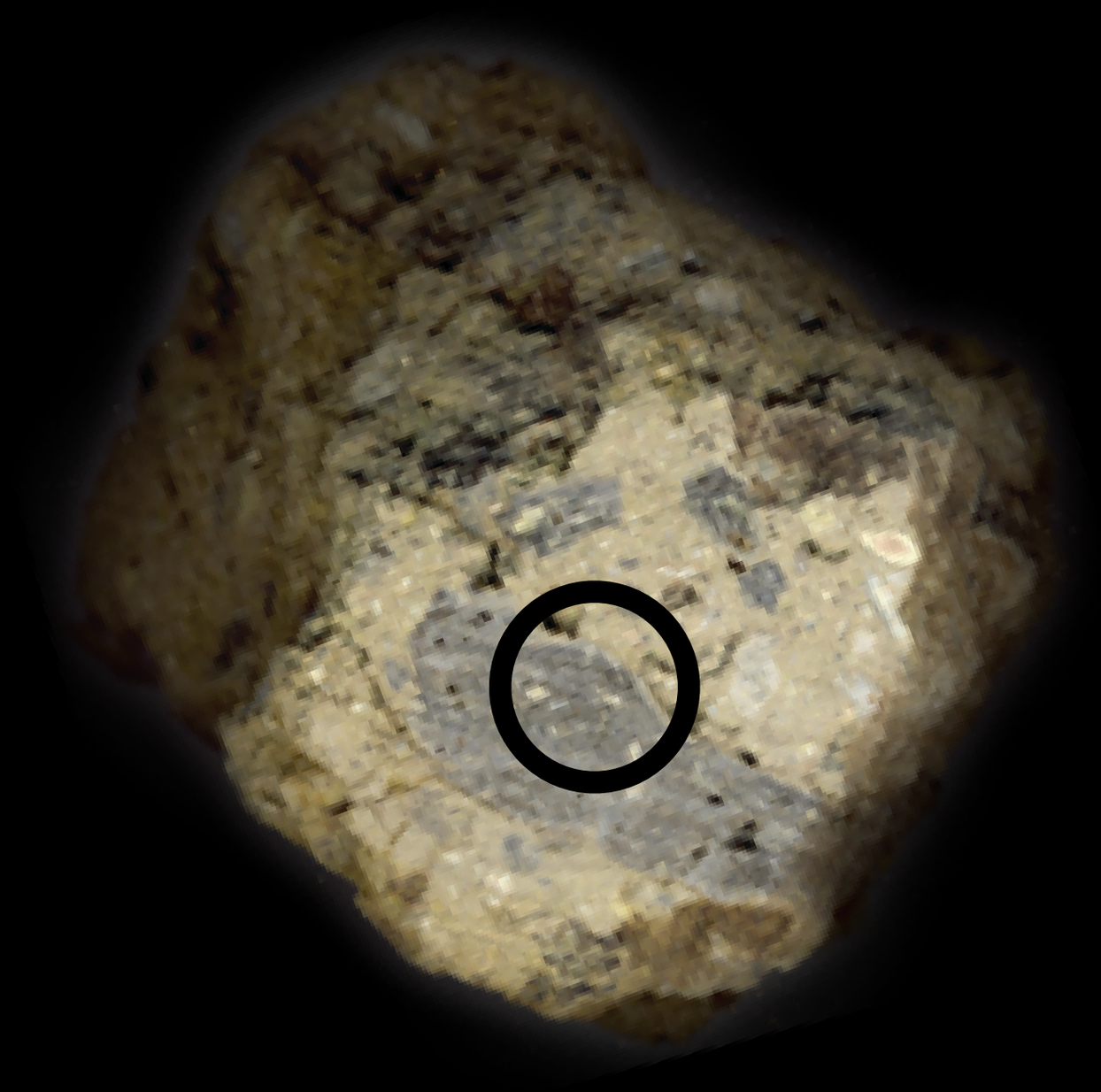
Geologic diversity and preservation



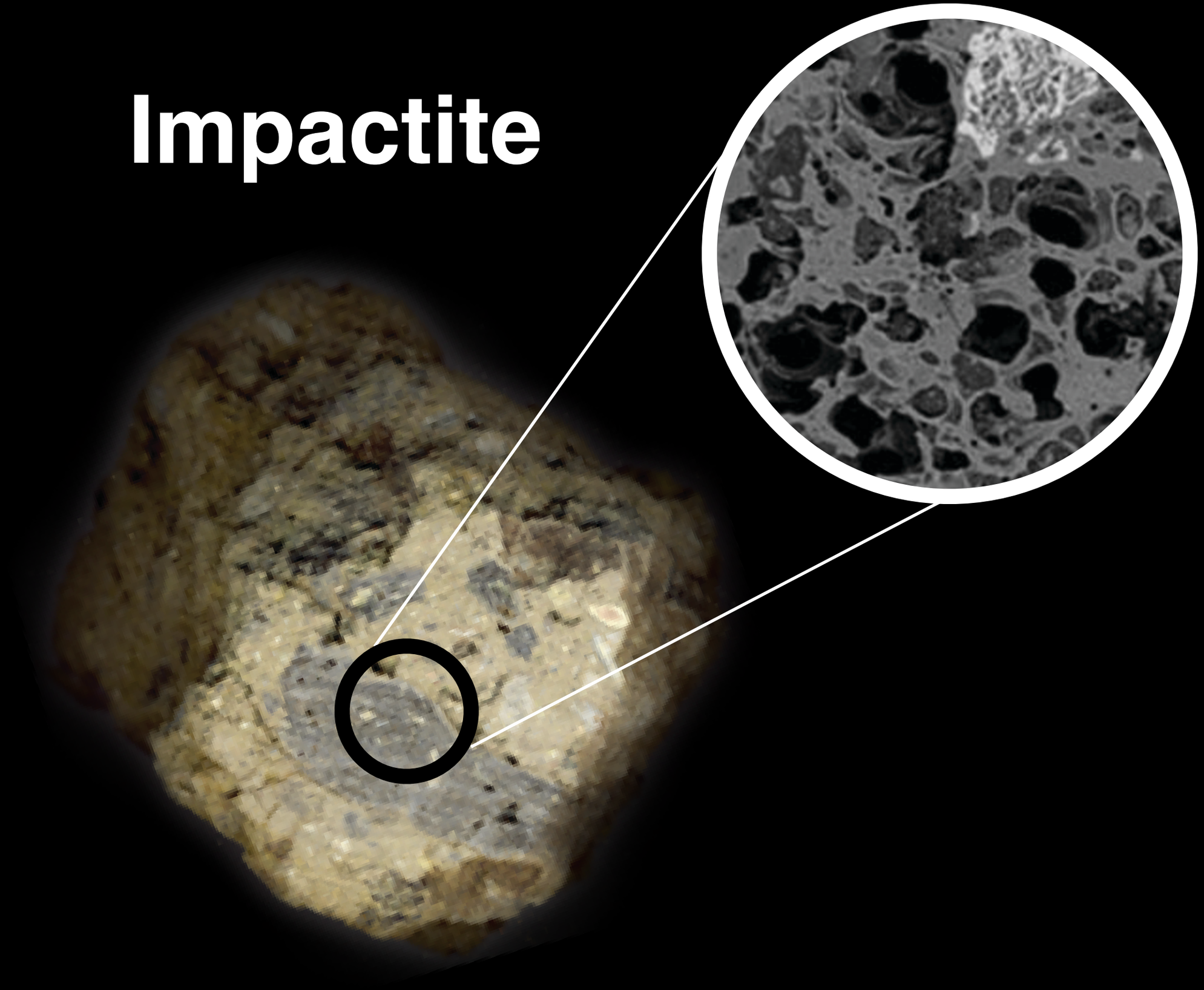
Impactite



Impactite

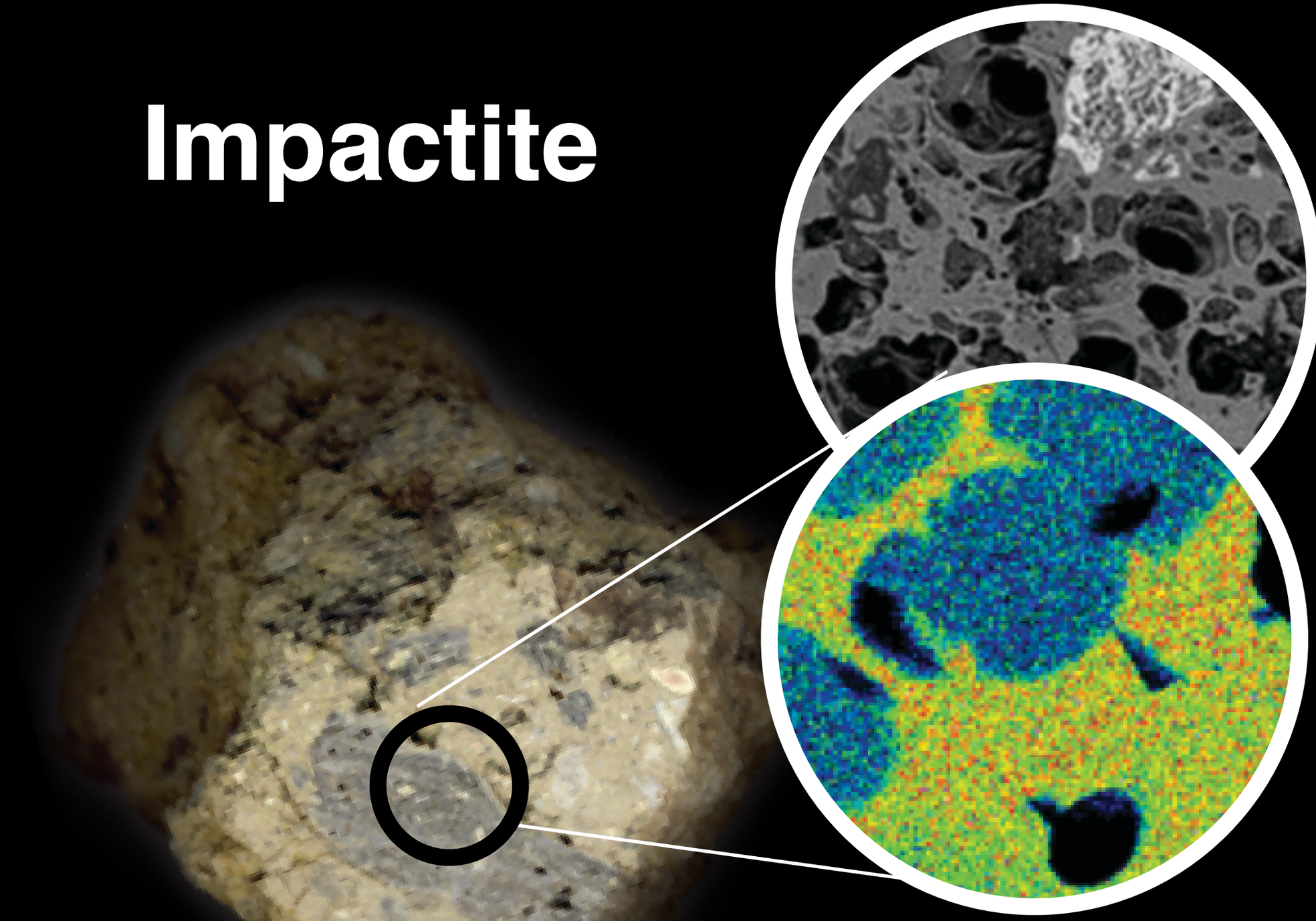


Impactite



porosity and permeability = habitats

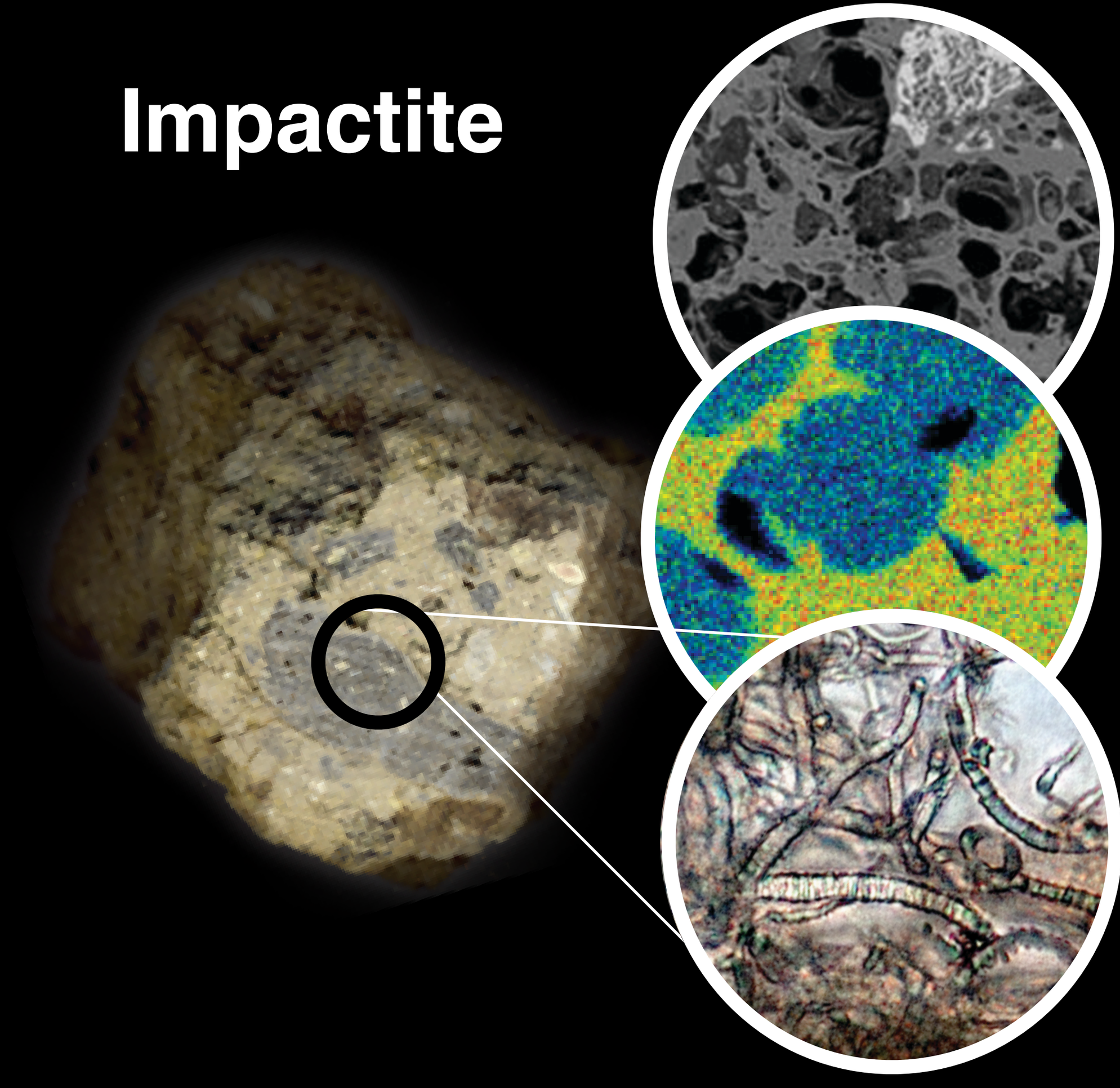
Impactite



porosity and permeability = habitats

geochemical heterogeneity = metabolic energy

Impactite

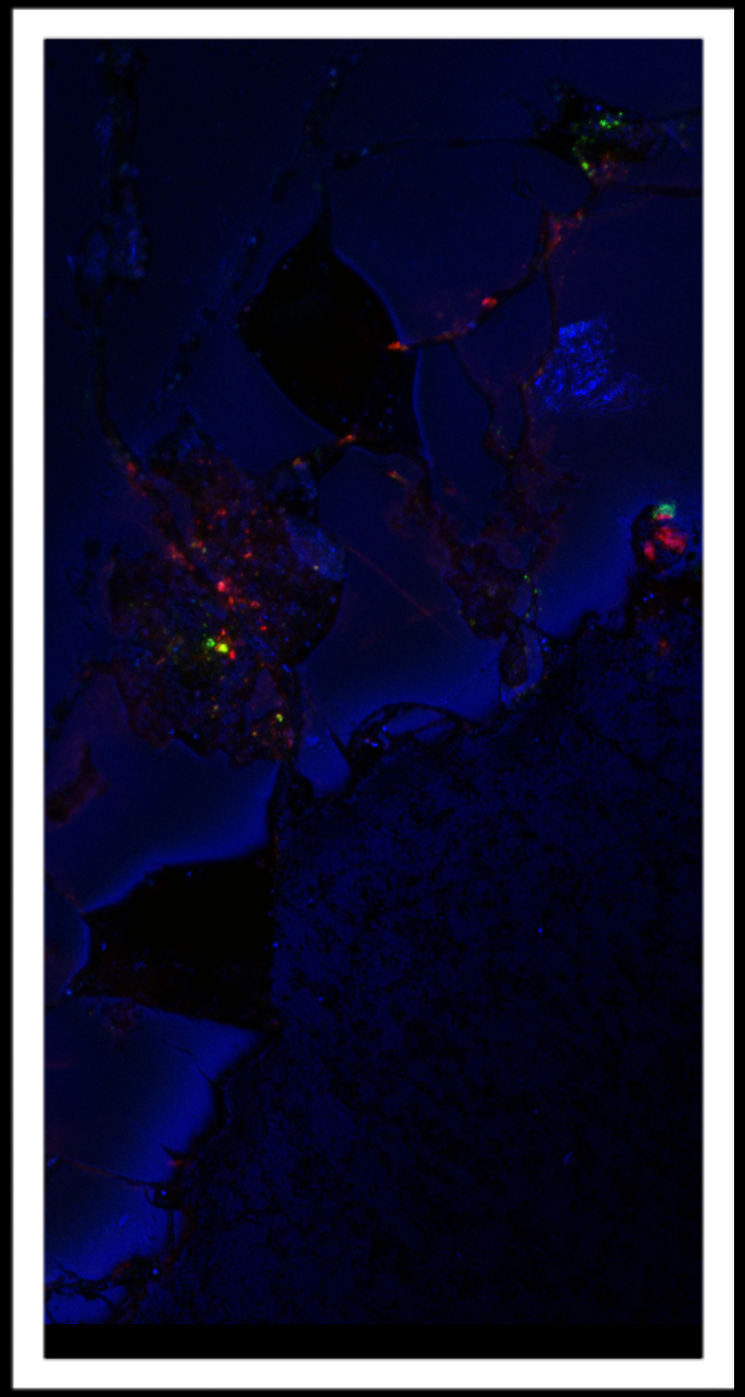


porosity and permeability = habitats

geochemical heterogeneity = metabolic energy

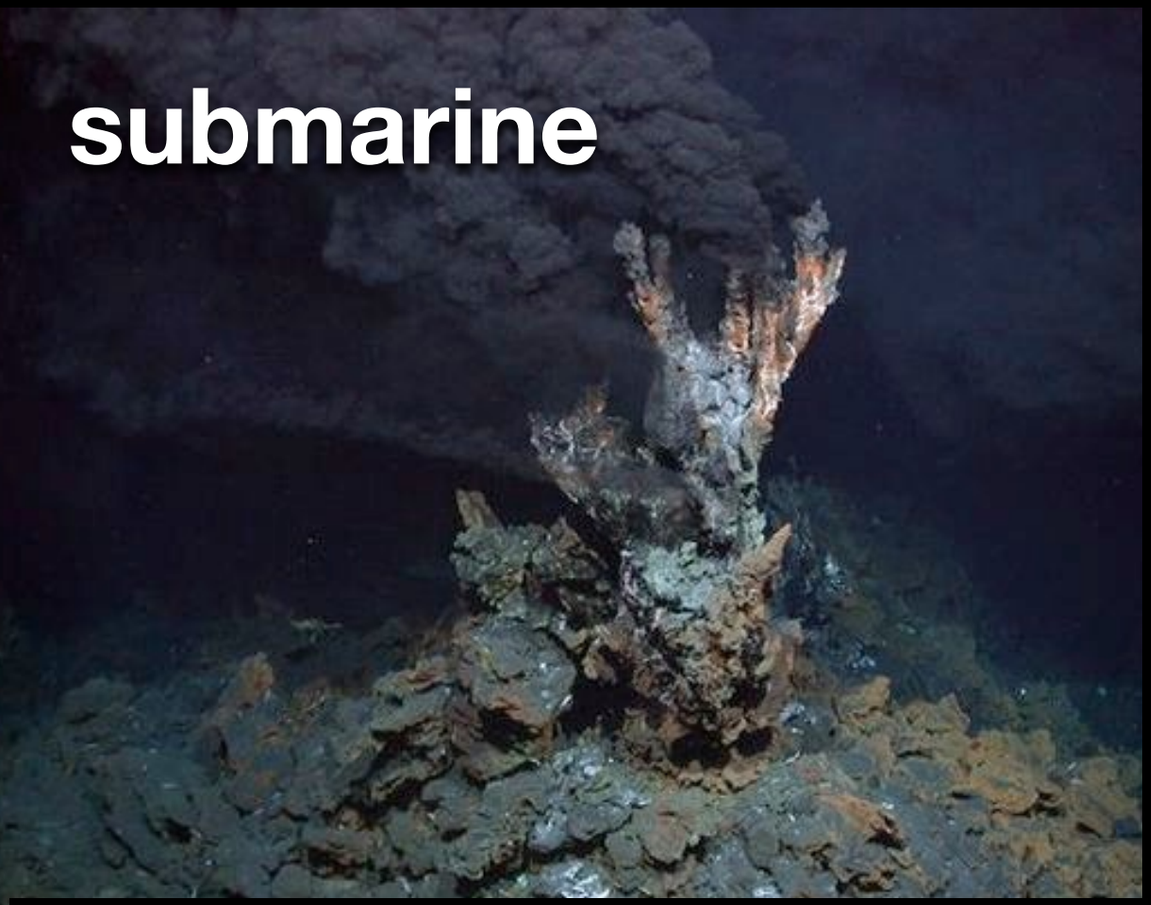
habitat + energy = colonization

Habitat Creation & Colonization for rock-hosted life

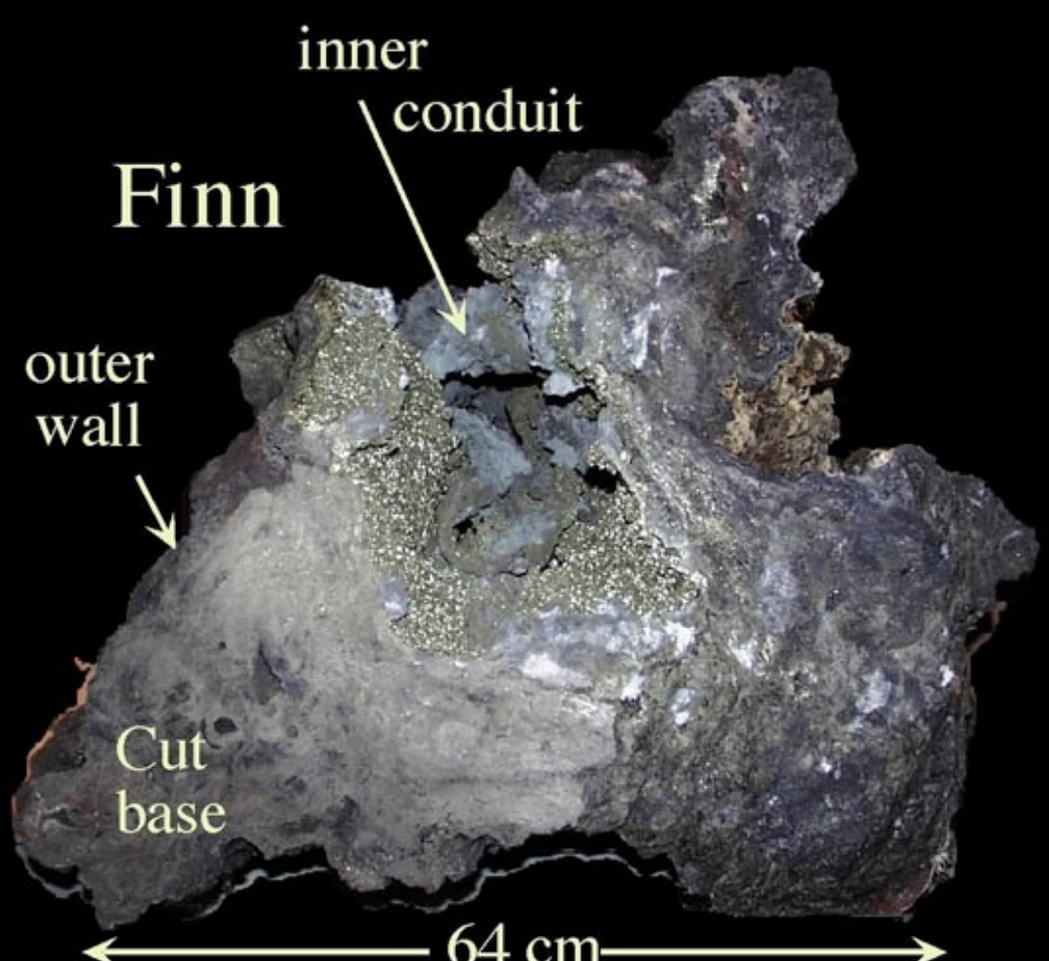


- energy disequilibria
- protective habitats
- niche division
- adaptive advantage

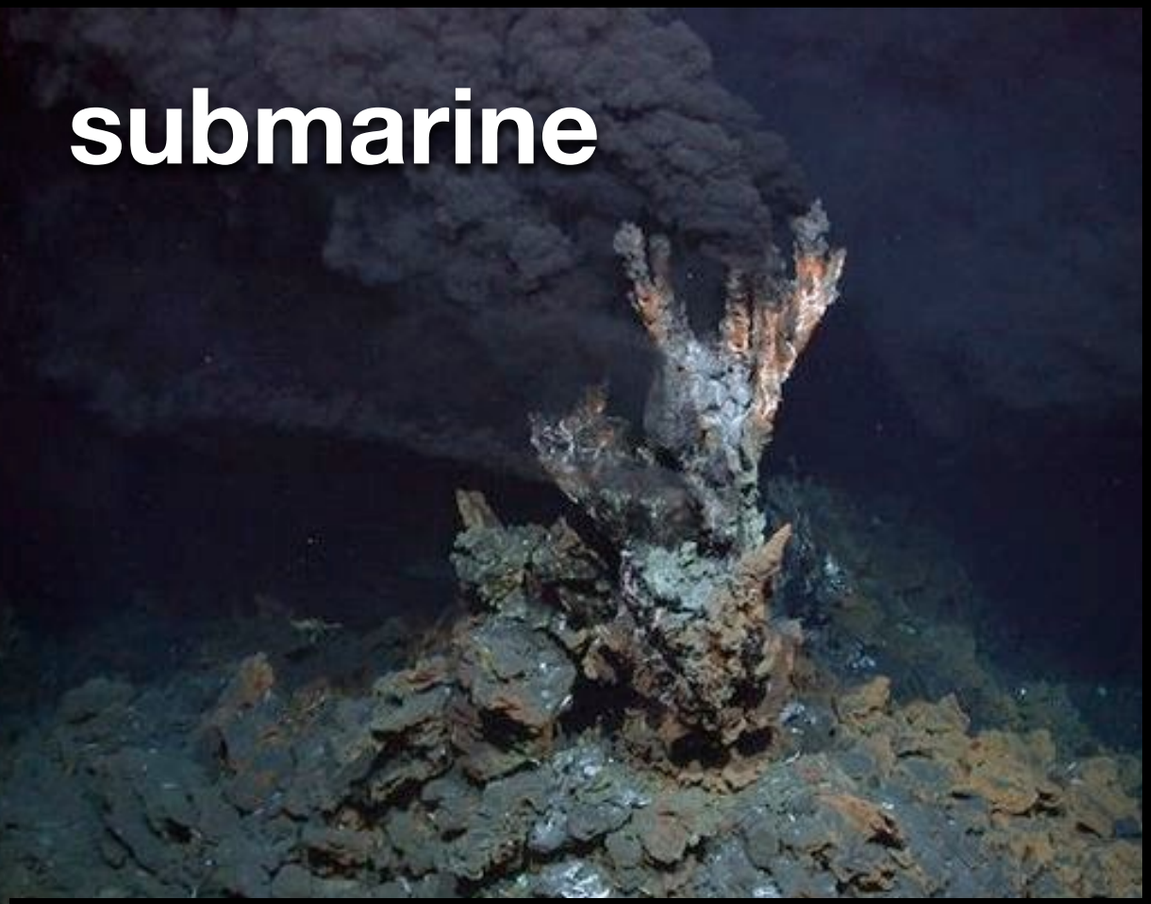
submarine



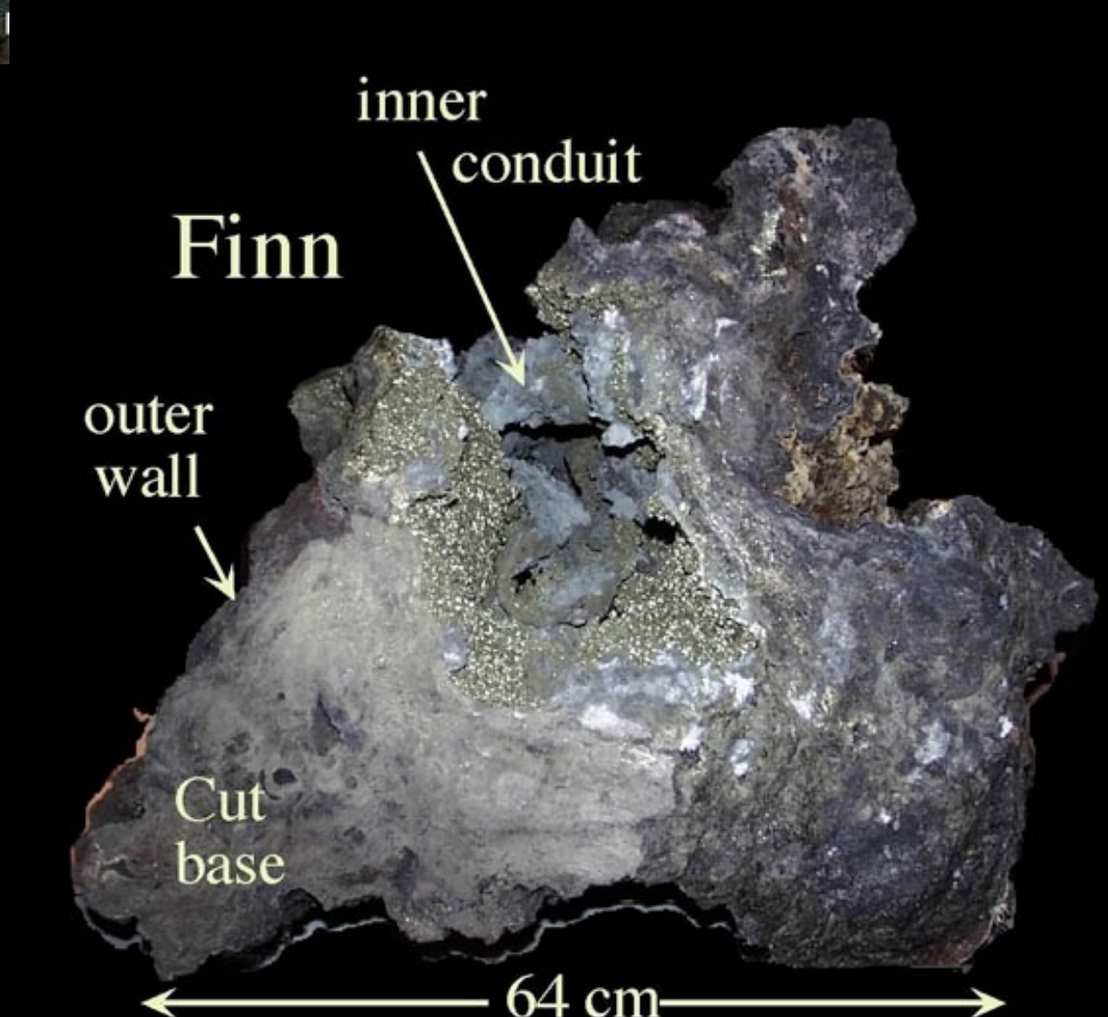
impact

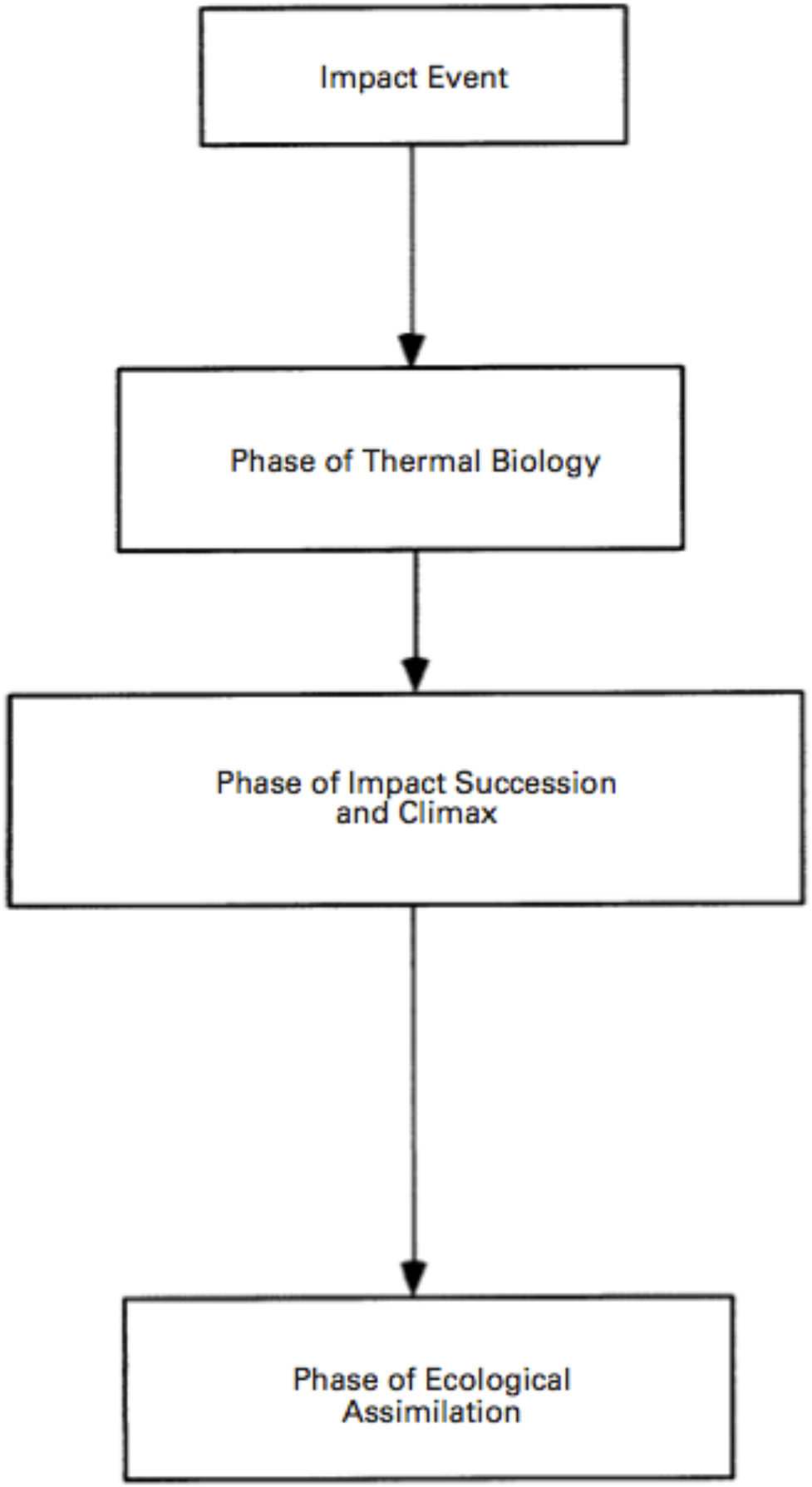


MARUM
Forschungszentrum
Ozeanränder
Universitat Bremen


submarine

impact


Finn
inner
conduit
outer
wall
Cut
base
64 cm



Major events associated with each phase

Quasi-complete sterilization of impact site occurs during event.

General features

Sites of hydrothermal activity at crater with associated microbial ecology.

General features

Formation and colonization of impact crater lake. Possible departure of lake waters after breach of crater rim lake(s) and/or evaporation and recolonization of paleolacustrine sediments.

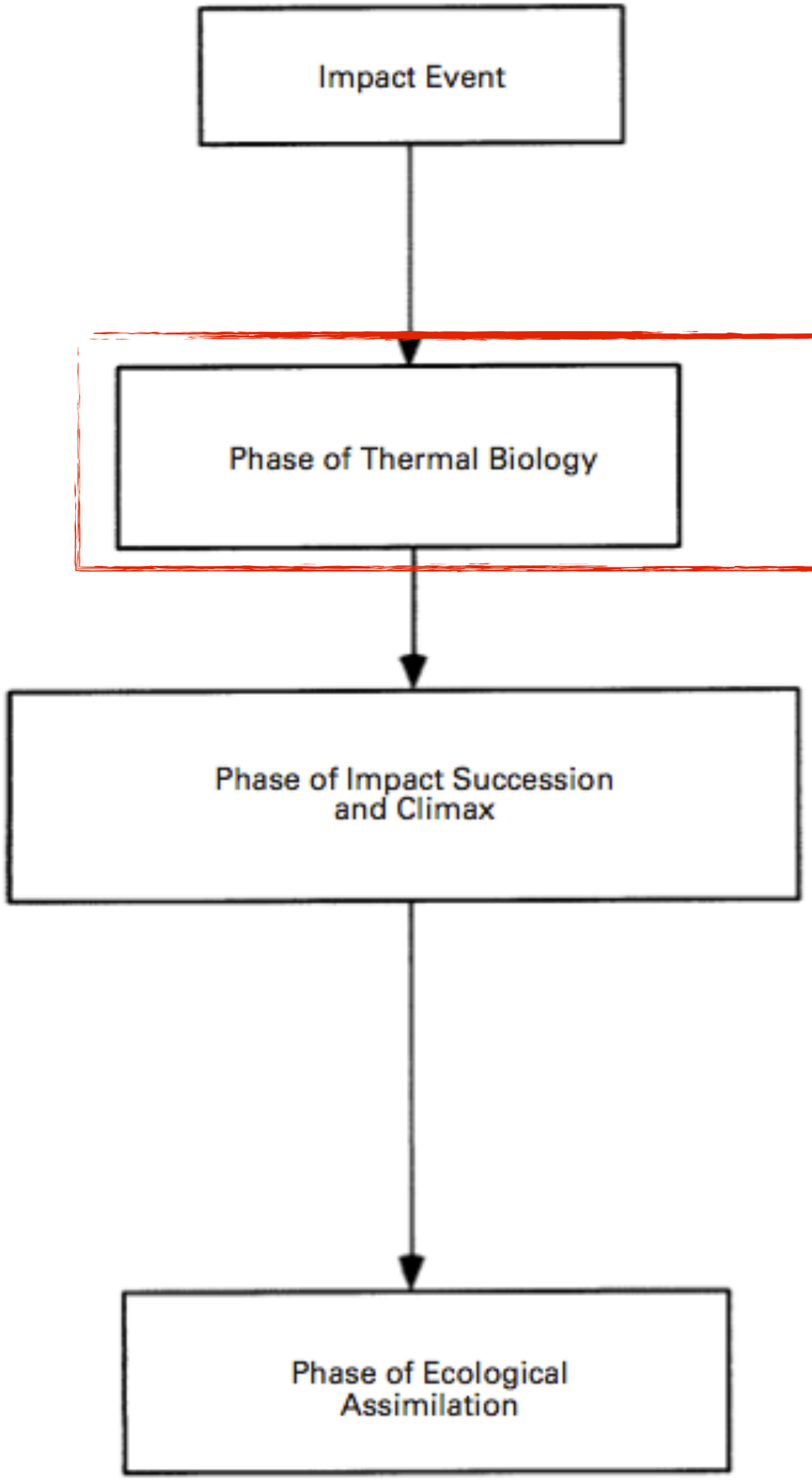
Where lake does not form, colonization can occur. on impact-generated substrata, e.g. impact breccia. In many biomes colononization of crater by vegetation can result in intracrater 'oasis', because of hydrologic depression.

At each of these stages the crater may reach a stage of climax ecology, which may be transitory.

General features

Crater is eroded or infilled. On land this results in loss of hydrologic depression. Impact crater ecosystems become indistinguishable from outlying regions.

In extreme assimilation, crater becomes heavily eroded or completely buried.



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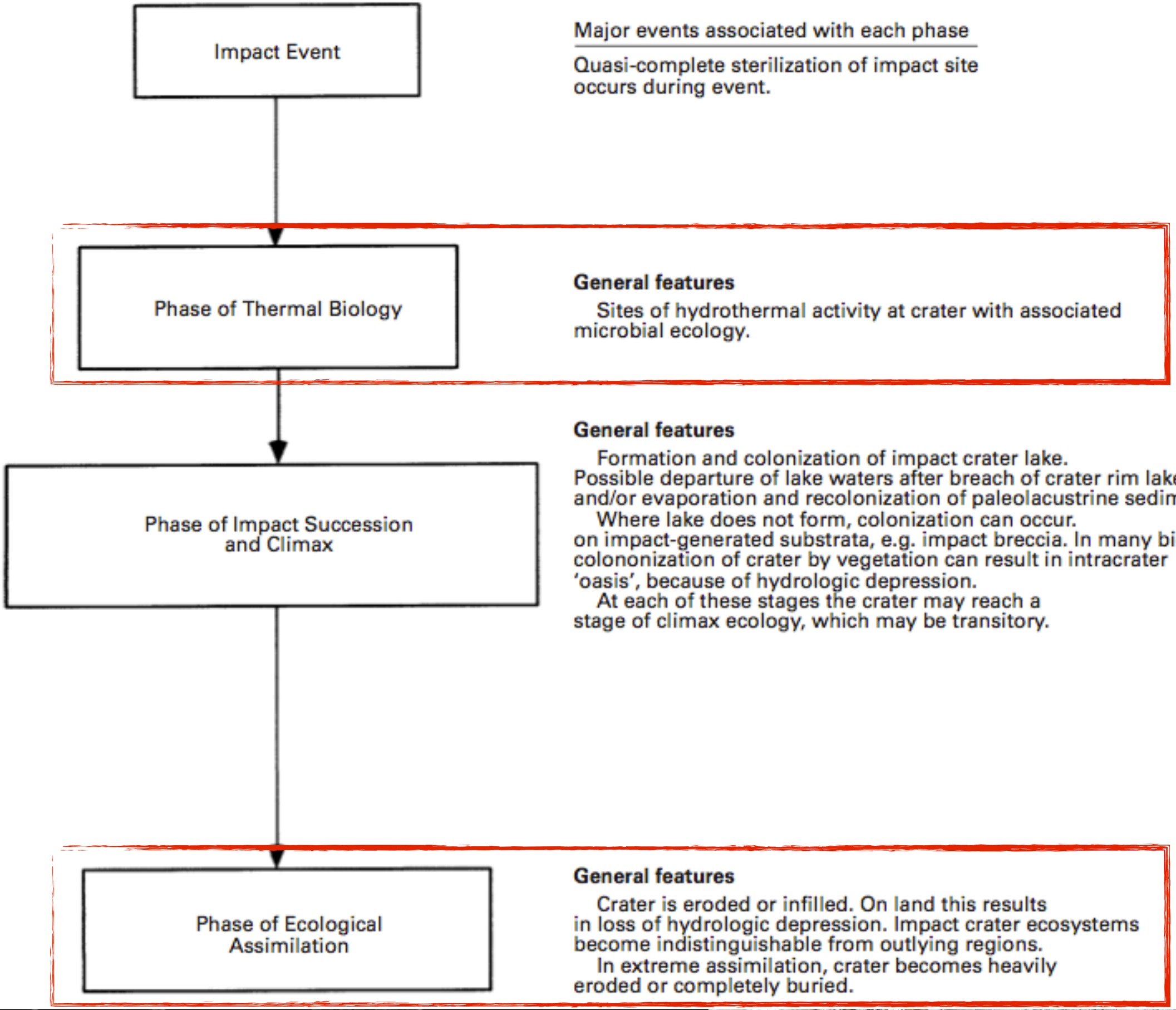
Impact Event
Major events associated with each phase
Quasi-complete sterilization of impact site occurs during event.
Phase of Thermal Biology
General features
Sites of hydrothermal activity at crater with associated microbial ecology.
Phase of Impact Succession and Climax
General features
Formation and colonization of impact crater lake. Possible departure of lake waters after breach of crater rim lake(s) and/or evaporation and recolonization of paleolacustrine sediments.
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Phase of Ecological Assimilation
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Impact Event

Major events associated with each phase

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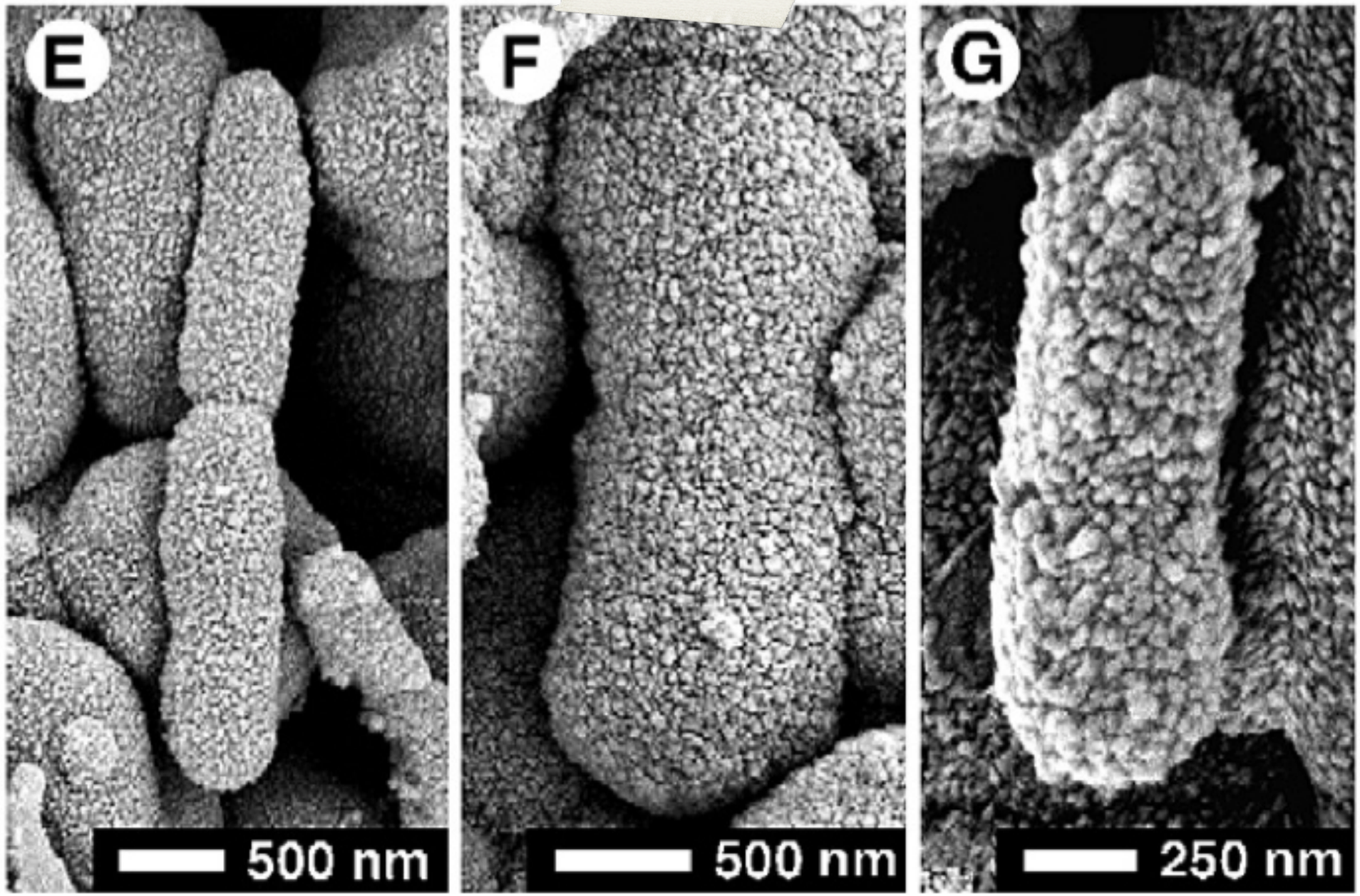

lake(s)
ediments.

y biomes
ter

Phase of Ecological Assimilation

General features

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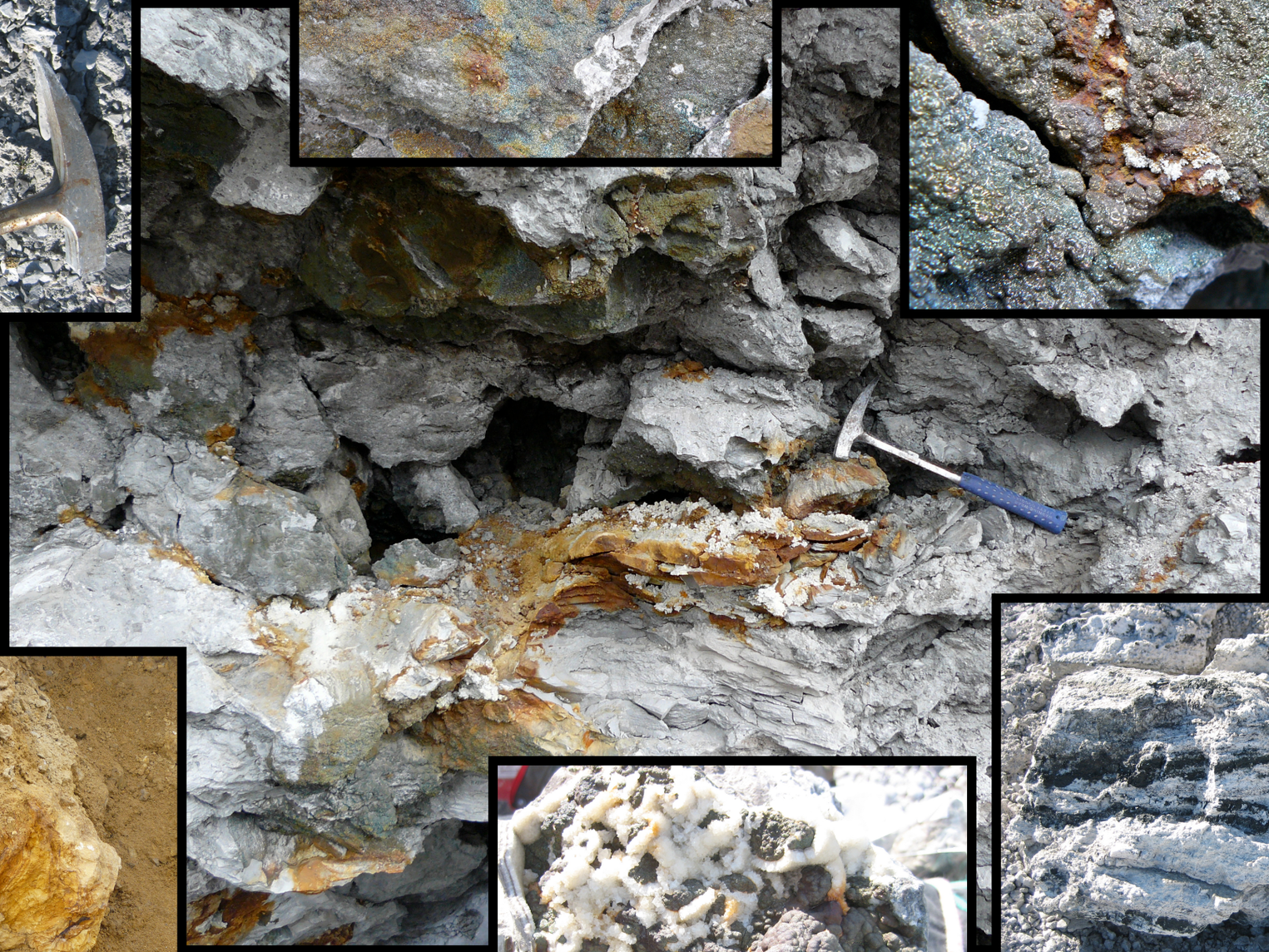
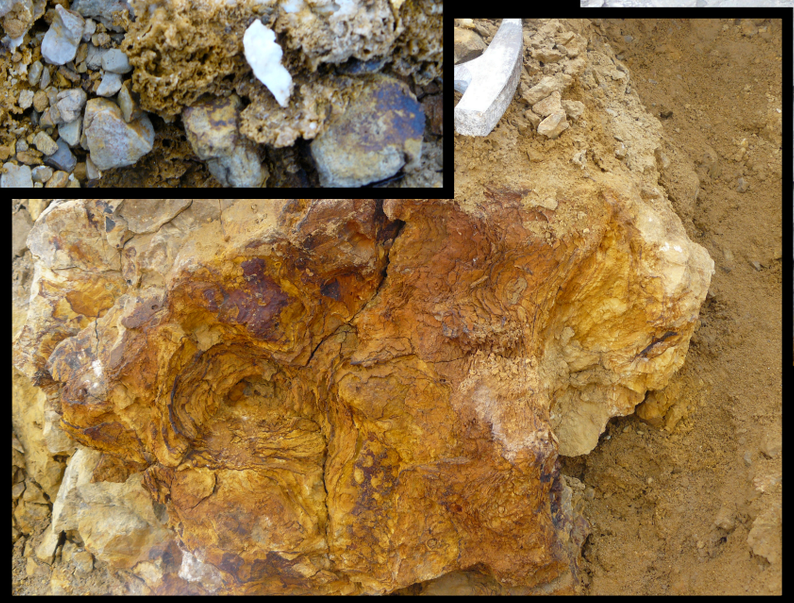
64 cm

Hydrothermal Minerals at Haughton





Endolithophiles: metabolism

organic C $\rightleftarrows$ CO_2

Quartz
(SiO_2)

Biotite
($K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$)
Extract: K^+, Fe^{3+}, $Fe(OH)_3$

Granite thin-section under crossed-polarized light. MacKenzie and Guilford, 1980.

Sodic Plagioclase
($Na[AlSi_3O_8]$)
extract: Na^+

Hornblende
($NaCa_2(Mg,Fe)_4AlSi_6Al_2O_{22}(OH,F)_2$)
extract: Ca^{2+}, Na^+, Fe^{3+}, $Fe(OH)_3$

Apatite
($Ca_5(PO_4)_3(OH,F,Cl)$)
extract: Ca^{2+}, PO_4^{3+}

Alkali Feldspar
($(K,Na)[AlSi_3O_8]$)
extract: K^+, Na^+

Anaerobic, chemiautolithotrophs use H_2 as an e- donor in energy yielding redox reactions

Microenvironment Feedback

fixation, volatilization

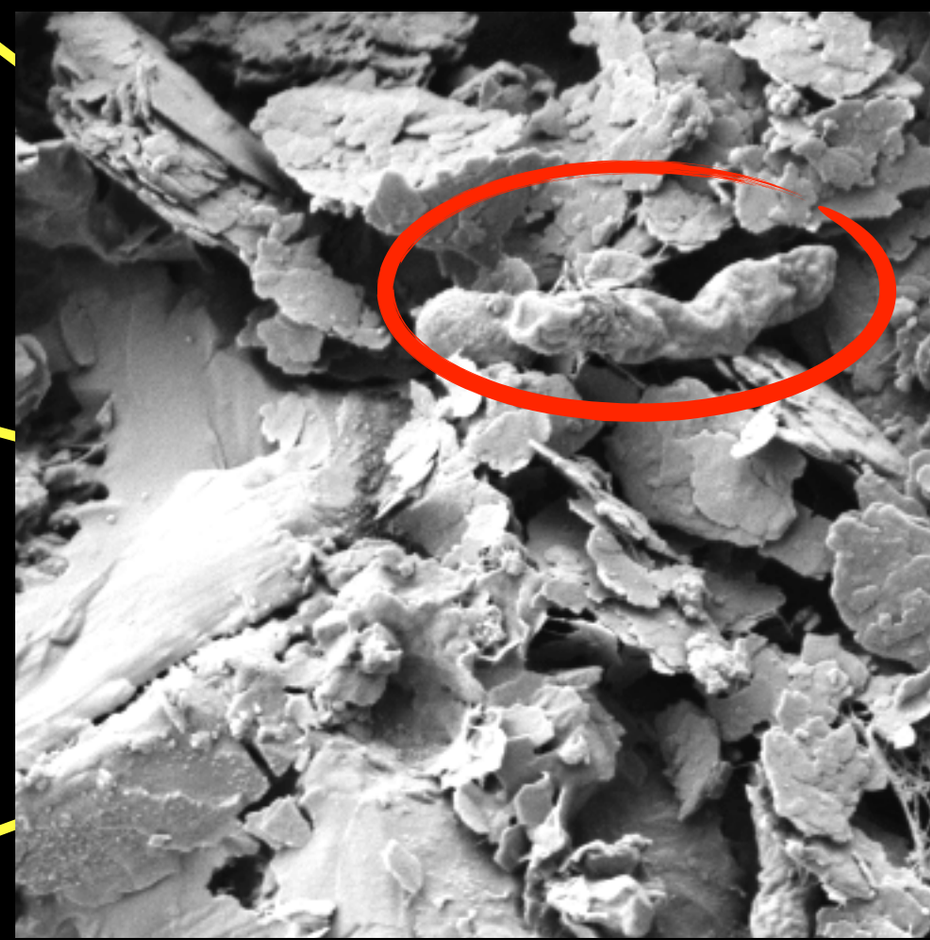
organic C $\rightleftarrows$ CO_2

Methylation

As, Se, Te, Sn, Pb, Hg

Chemolithotrophic leaching

H+, pH changes, Fe(III), SO_4^{2-}



Redox (im)mobilization

(Fe(III) - Fe(II)
Mn(IV) - Mn(II)

Chemo-organotrophic leaching

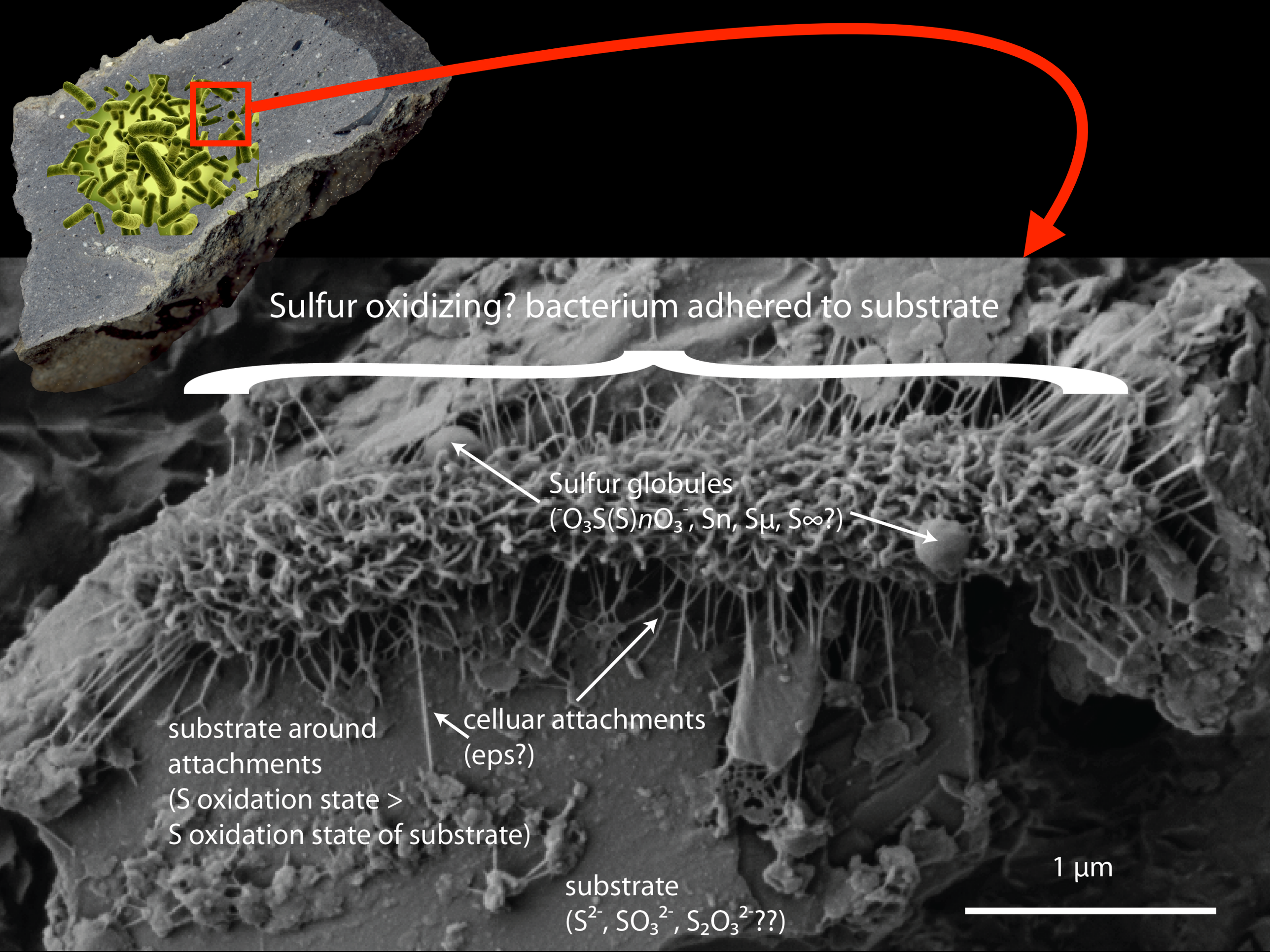
H+, siderophores, organic acids, metabolites

Biocorrosion
Biosoption

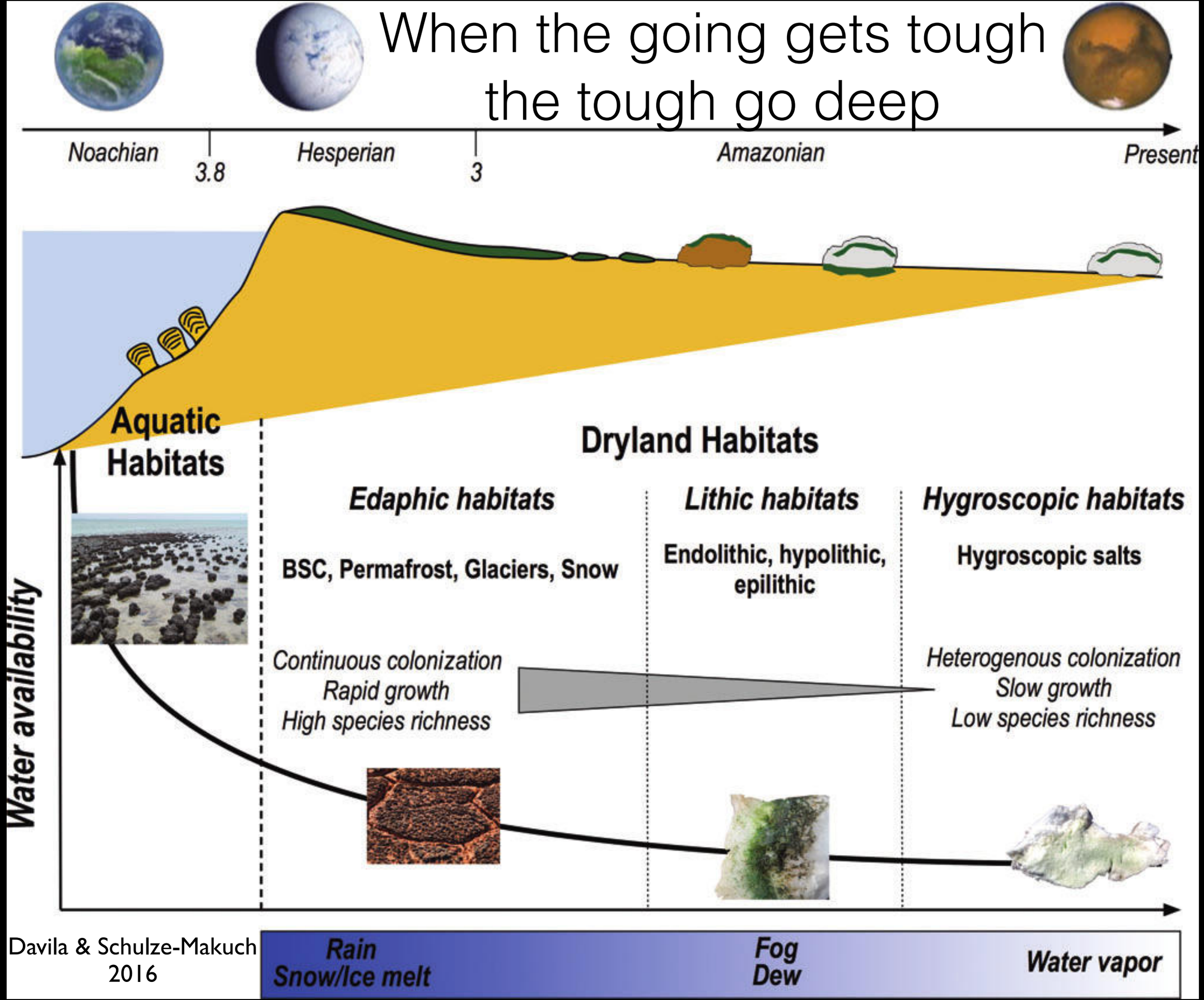
Metals

mineral bioweathering biomineralization

chemistry determines colonization
colonization affects chemistry


Sulfur oxidizing? bacterium adhered to substrate
Sulfur globules
($^{-}O_3S(S)nO_3^{-}$, Sn, Sμ, S∞?)
celluar attachments
(eps?)
substrate around
attachments
(S oxidation state >
S oxidation state of substrate)
substrate
(S^{2-}, SO_3^{2-}, $S_2O_3^{2-}$??)
1 μm

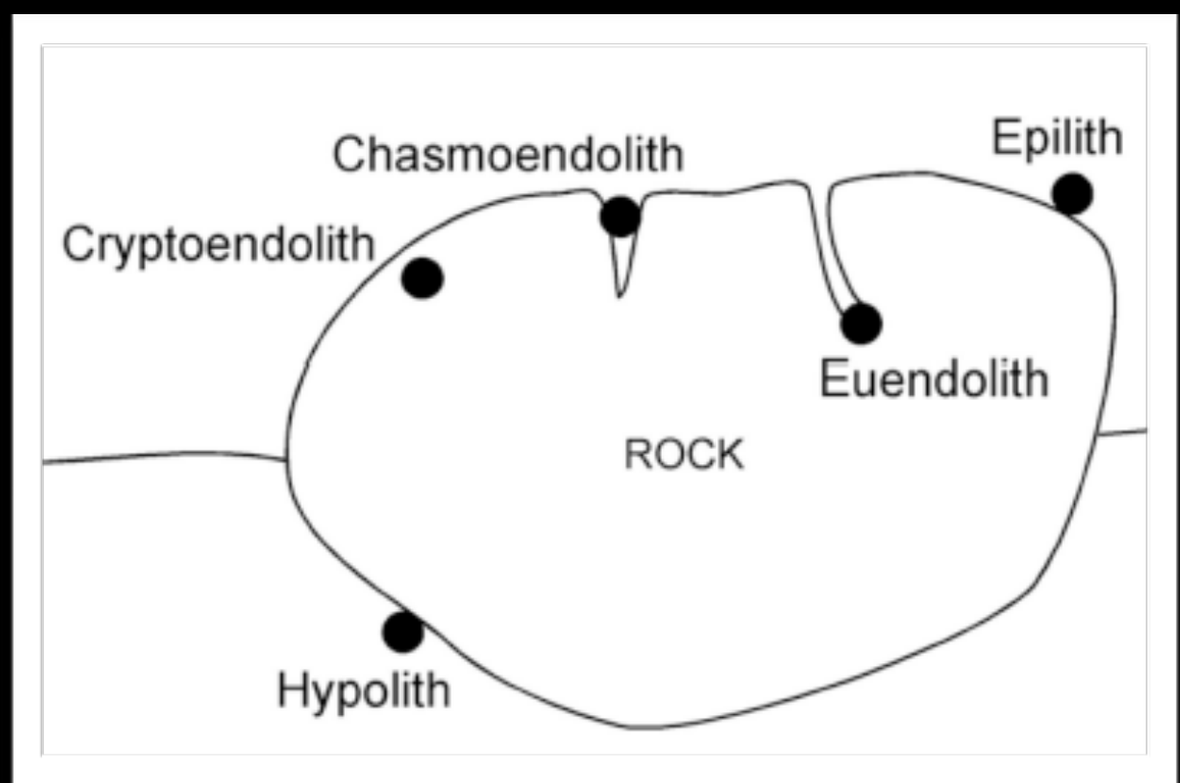
When the going gets tough the tough go deep



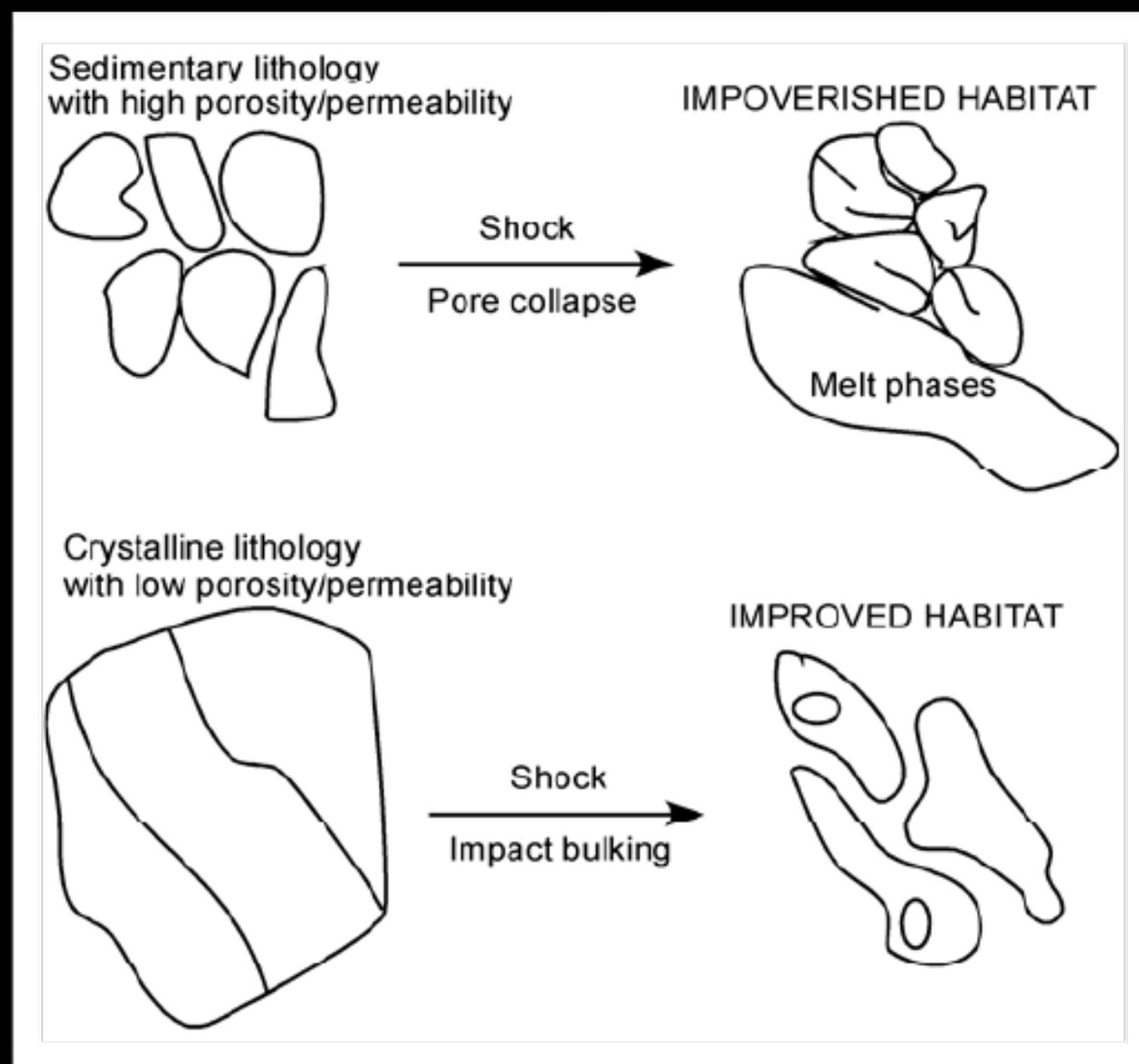
Davila & Schulze-Makuch 2016

Endolithic Environments

Alteration of target rocks can have both beneficial and detrimental effects to endolithic habitats



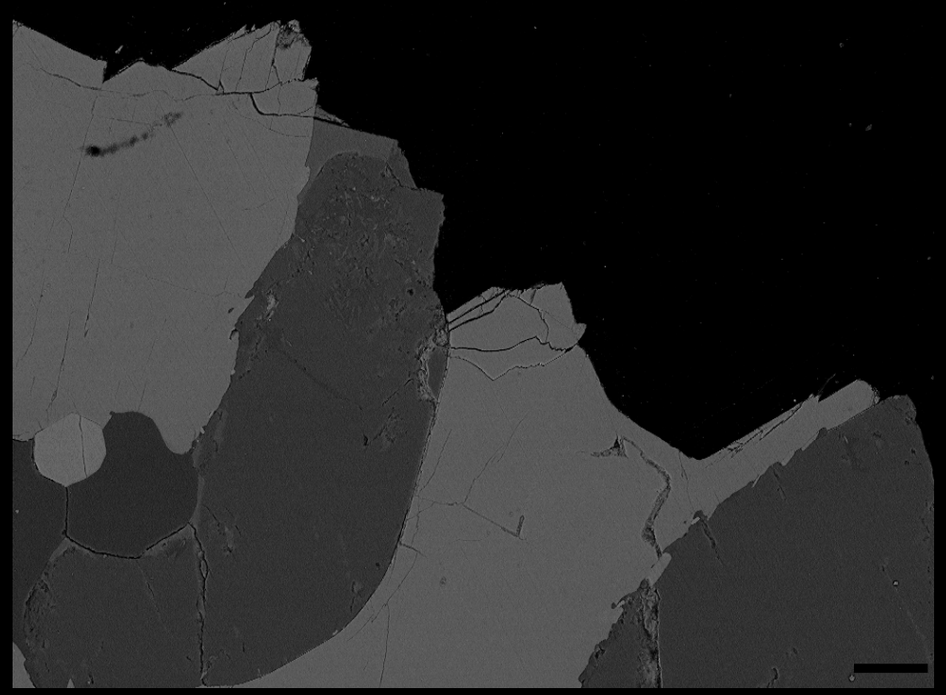
Schematic representation of endolithic habitats (Cockell, 2007)



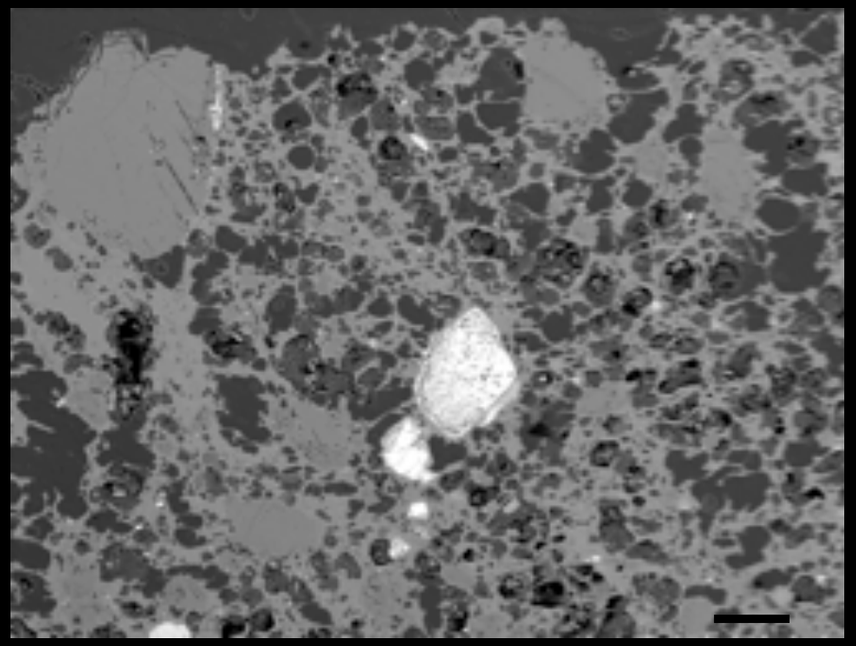
Differential effects of shock-metamorphism on target lithologies (Cockell, 2007)

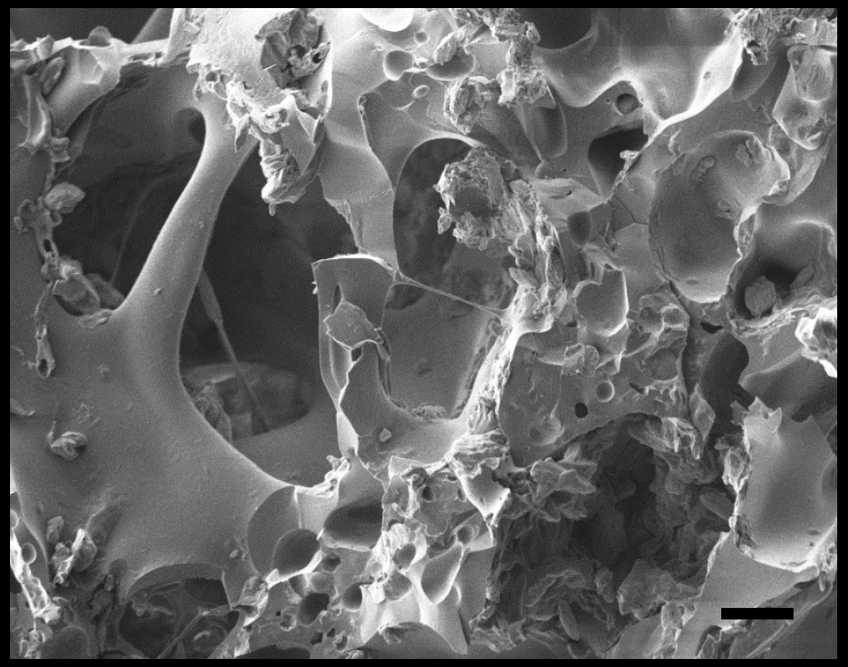
crypto- and chasmo-endoliths

- increase in porosity
- increase in pore space
- increase in translucence

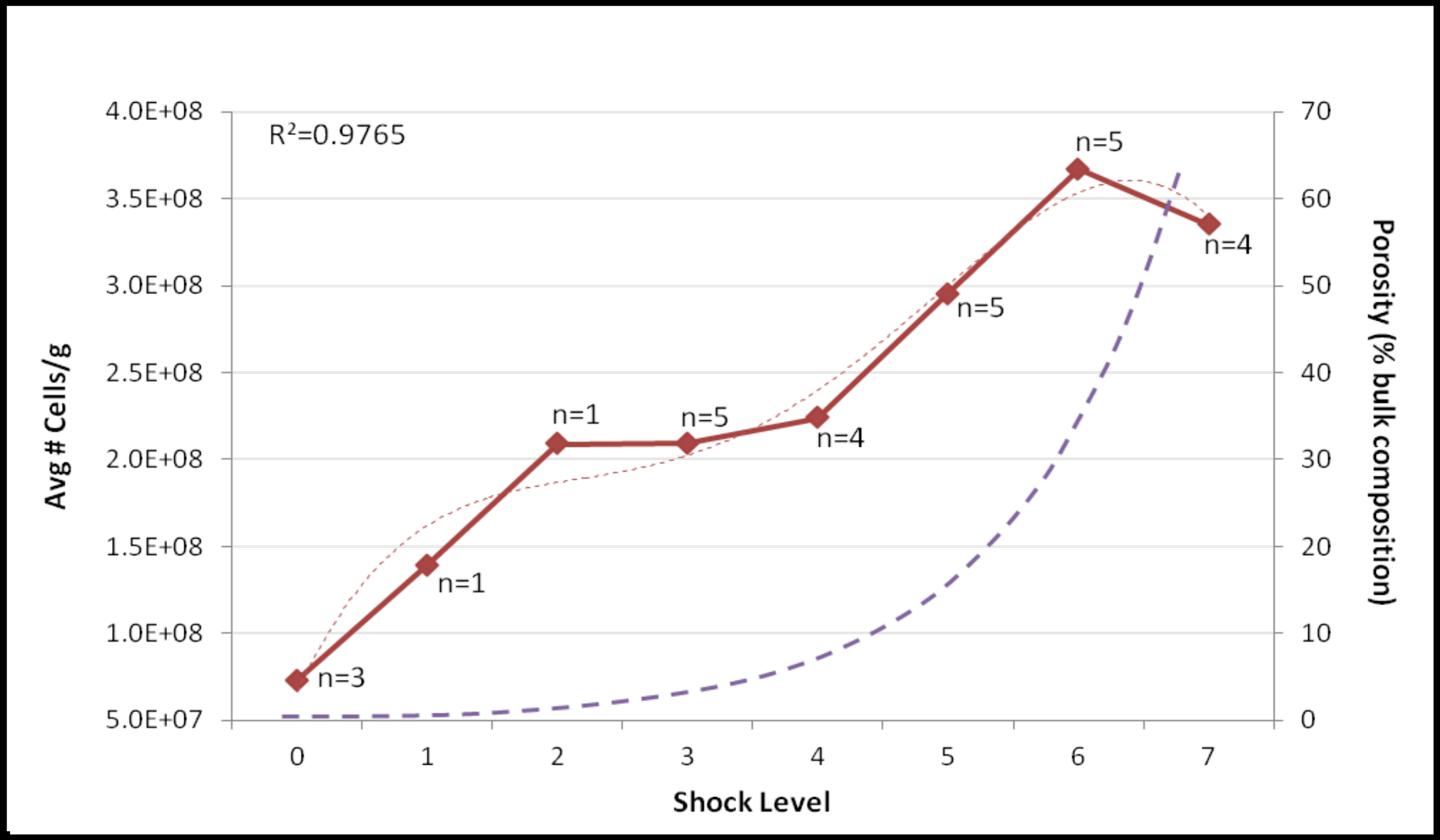


Pontefract et al., 2014





crypto- and chasmo-endoliths



Pontefract et al., 2014

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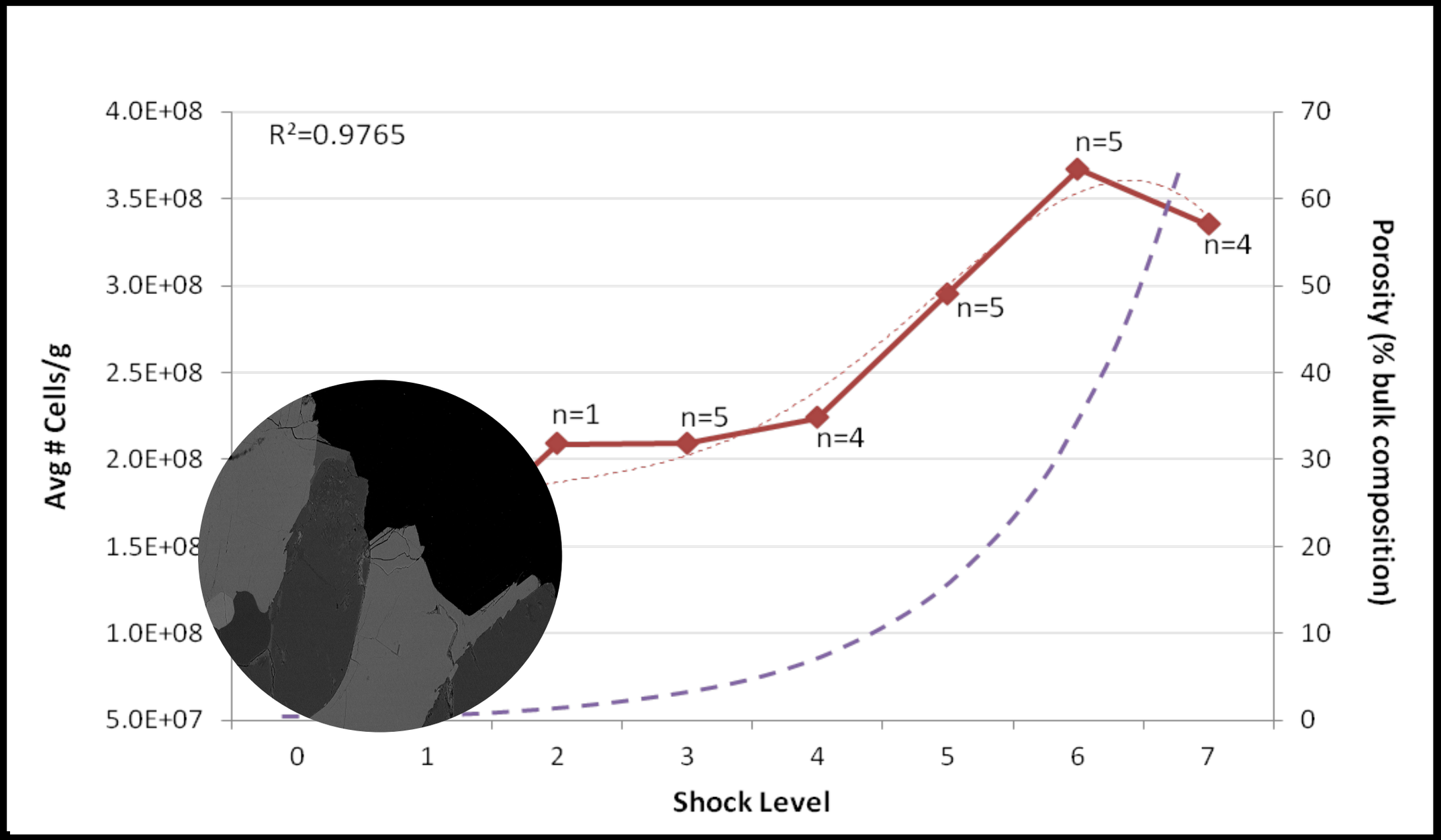

Pontefract et al., 2014

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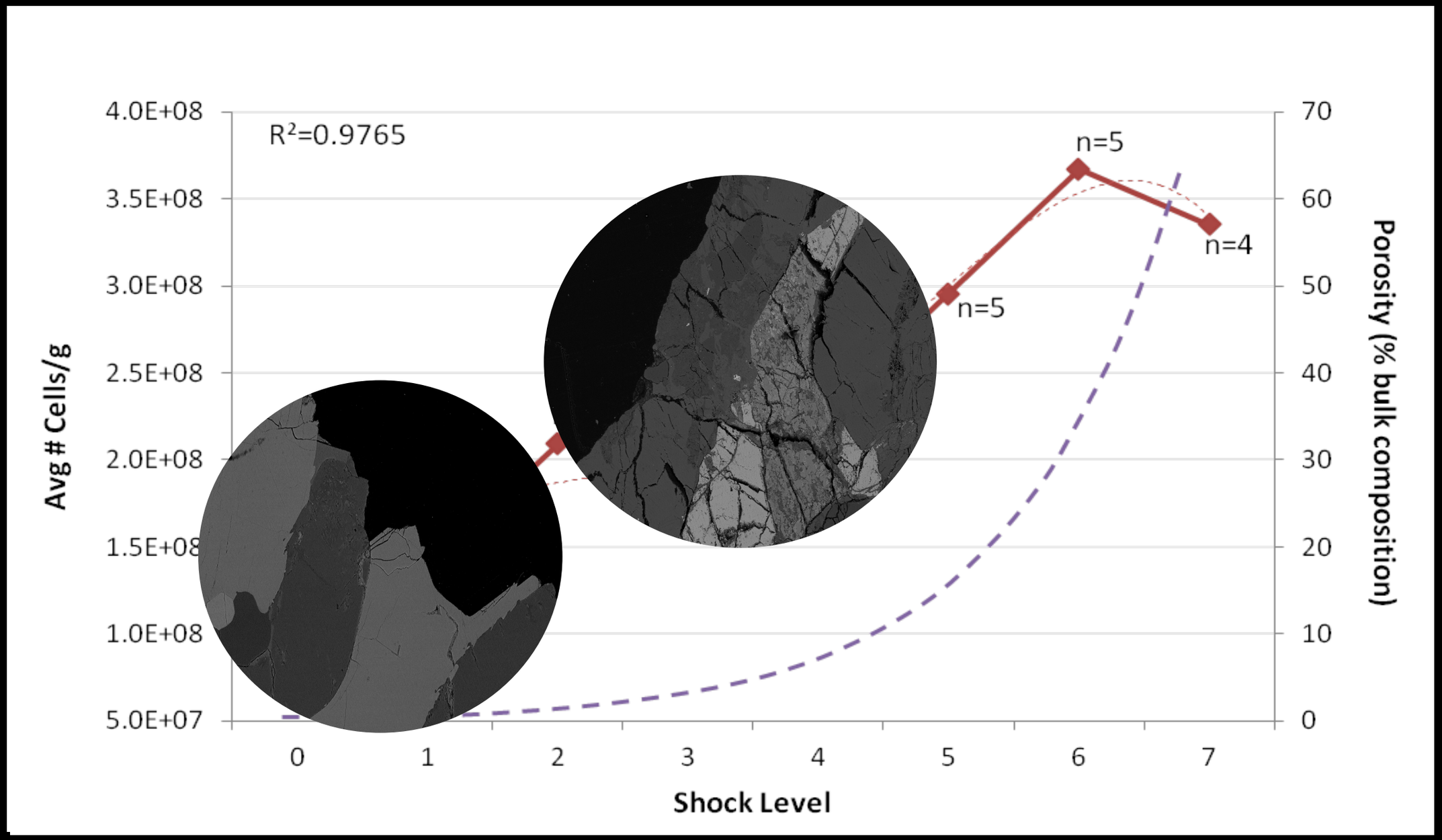

Pontefract et al., 2014

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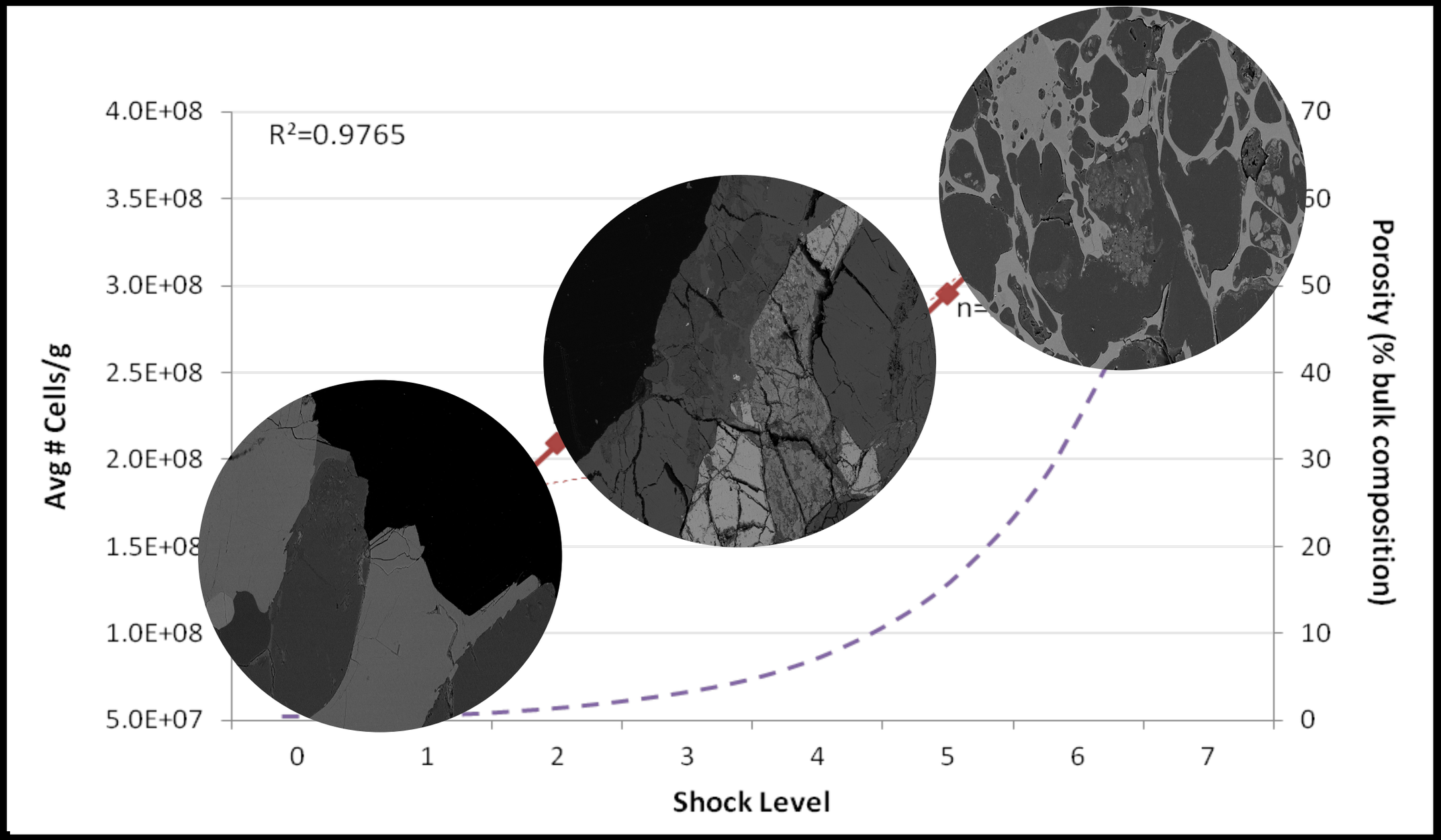

Pontefract et al., 2014

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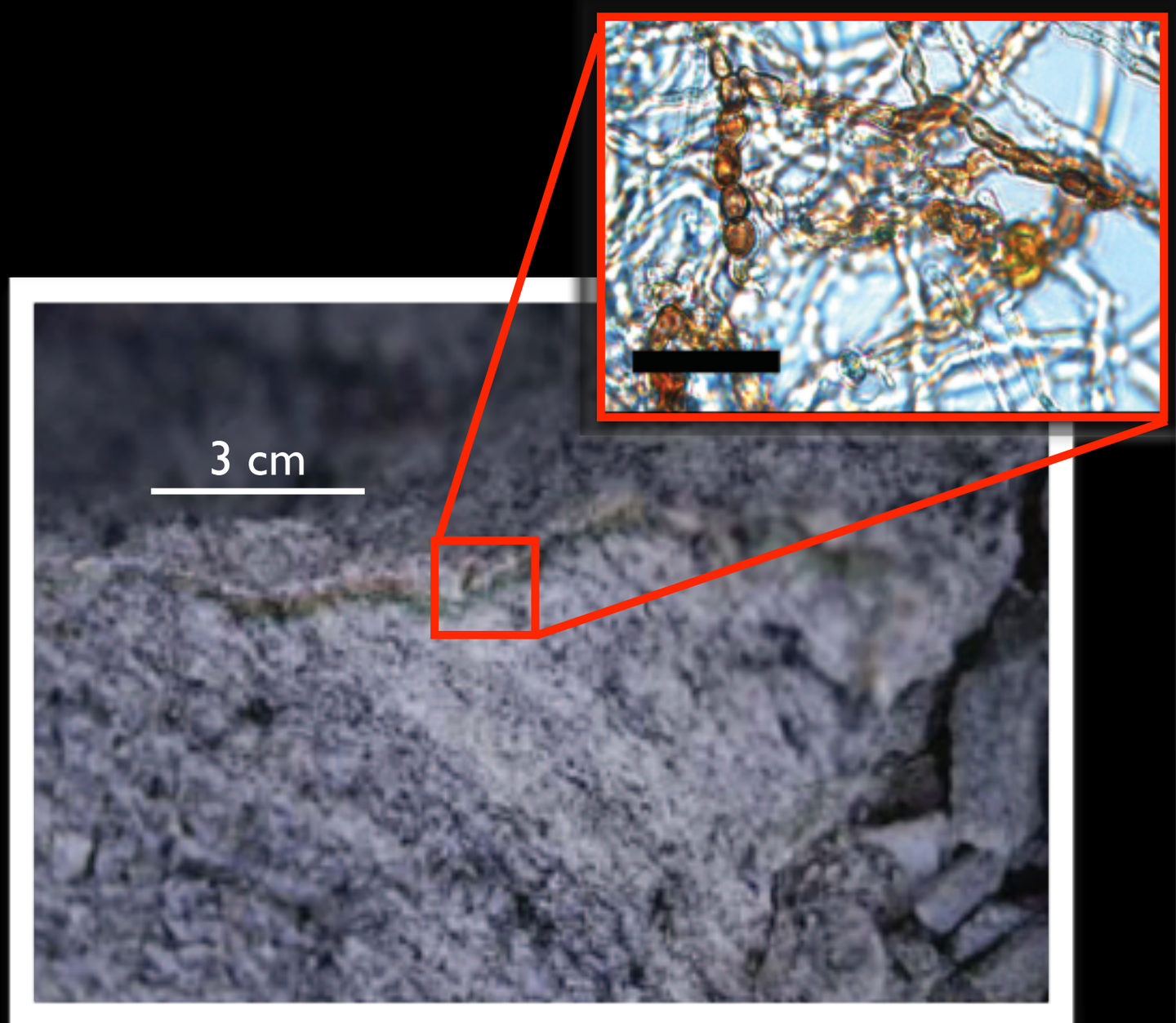
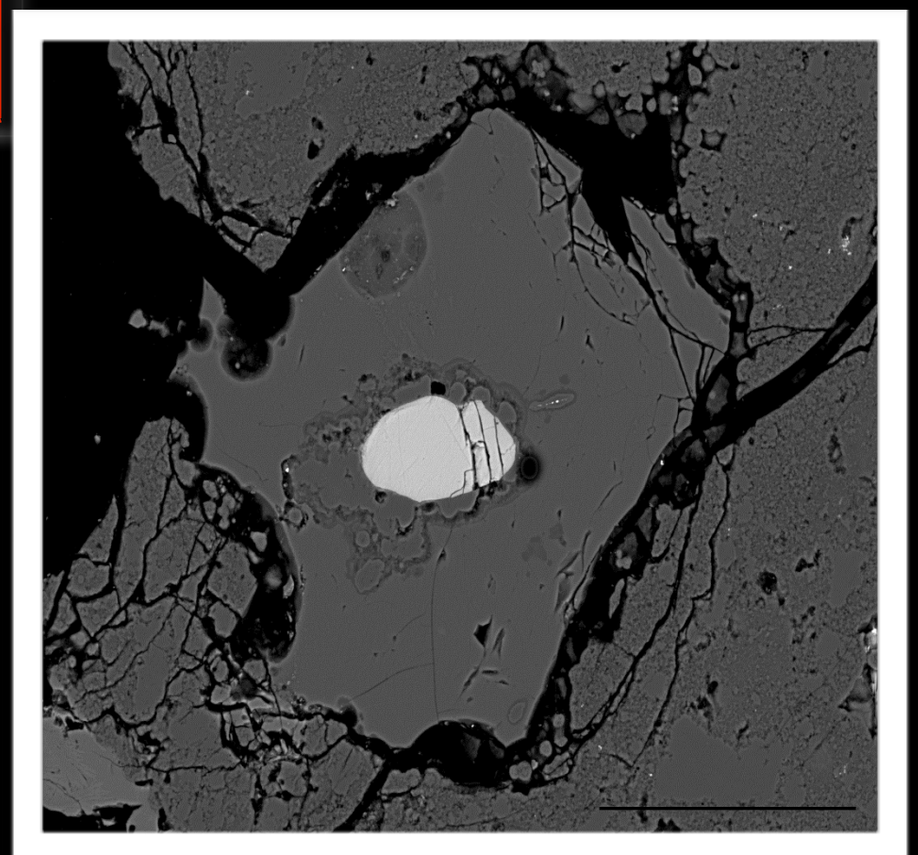
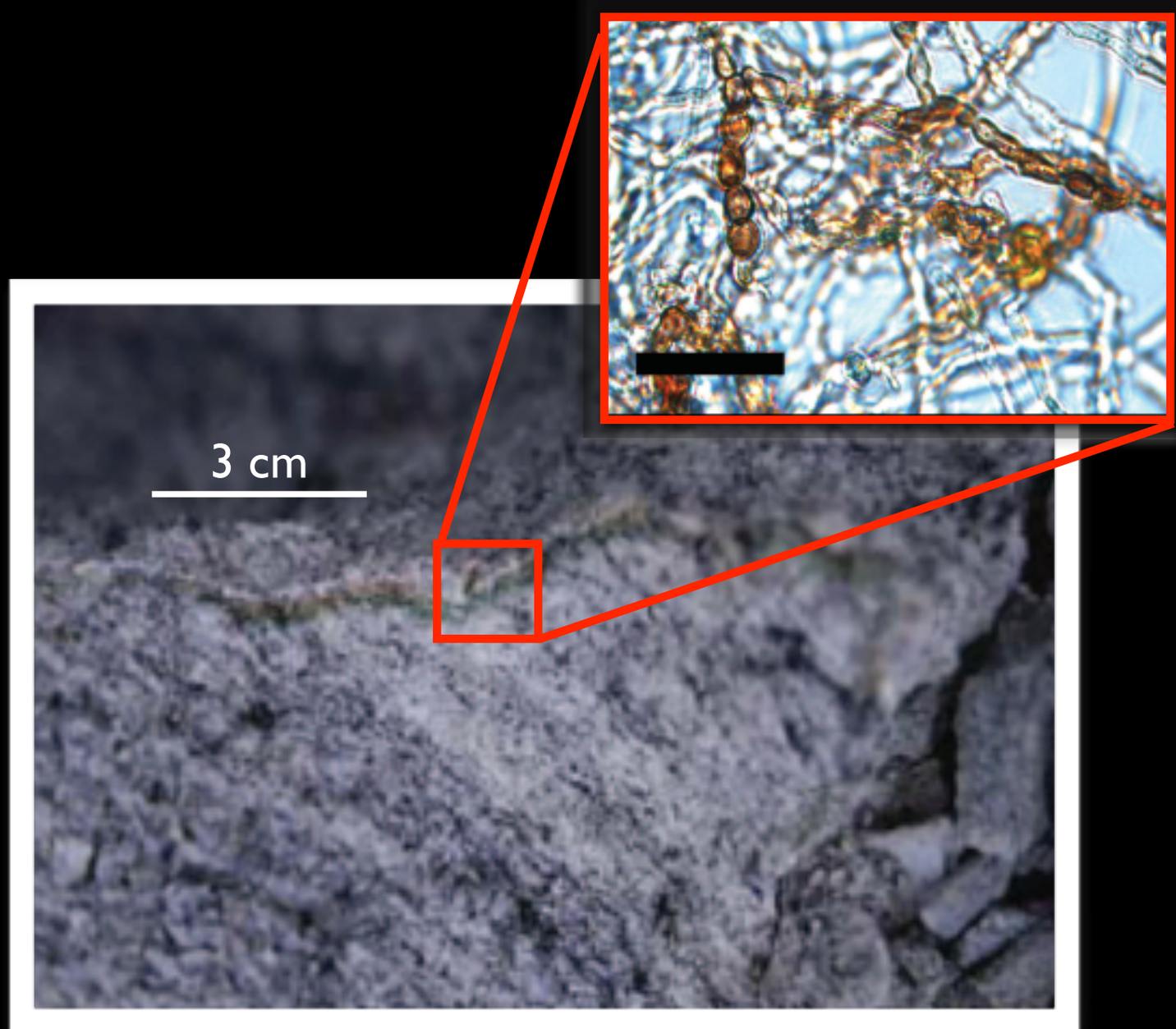


Cockell, 2005; 2006

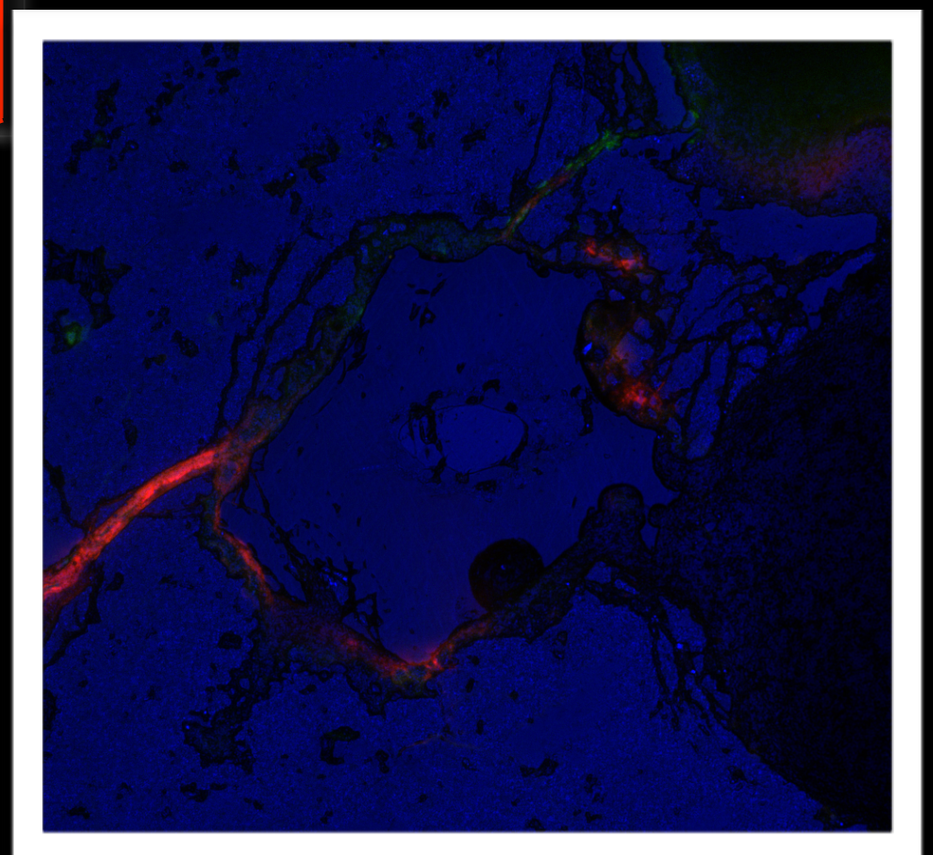


Pontefract, 2013

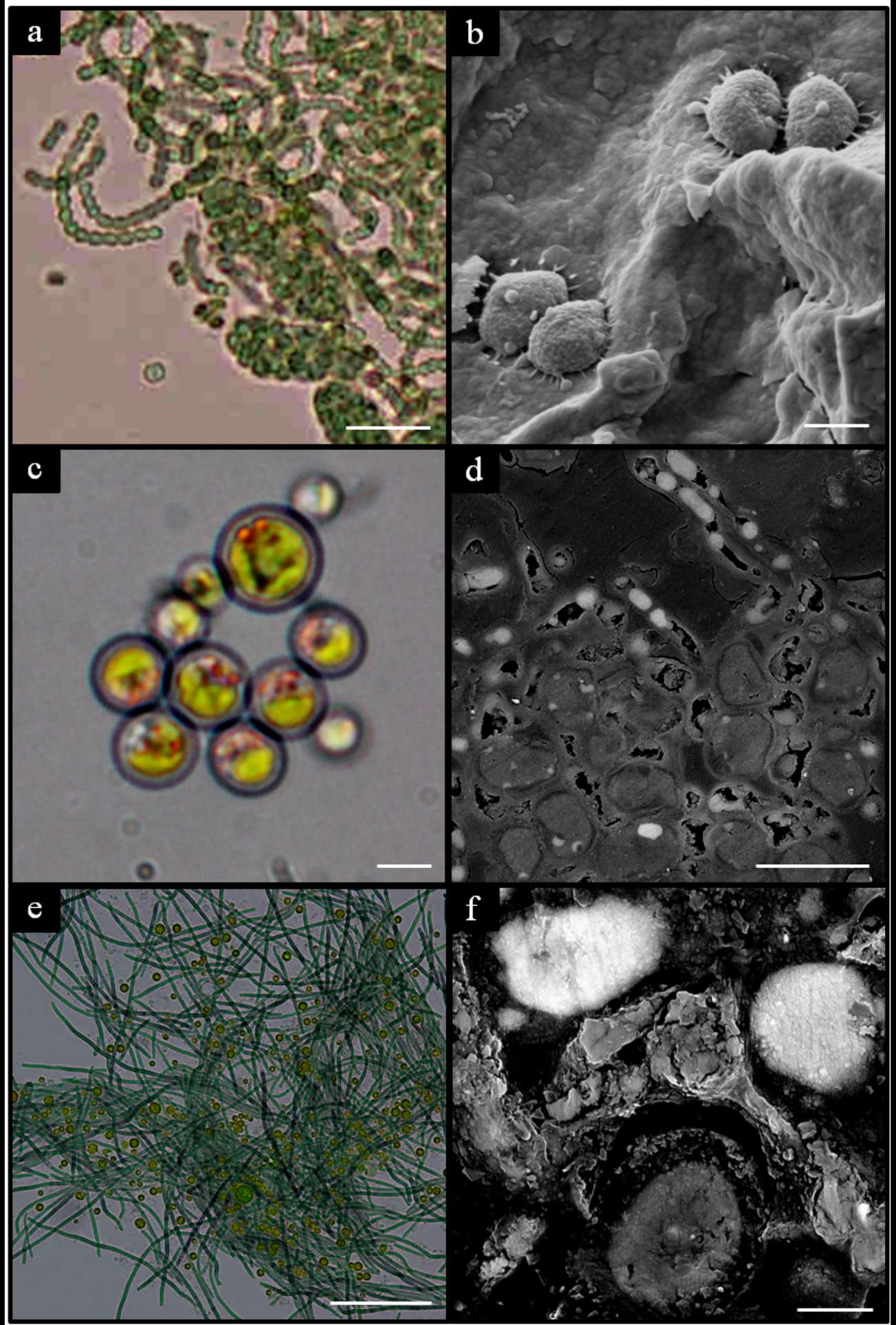
crypto- and chasmo-endoliths



Cockell, 2005; 2006



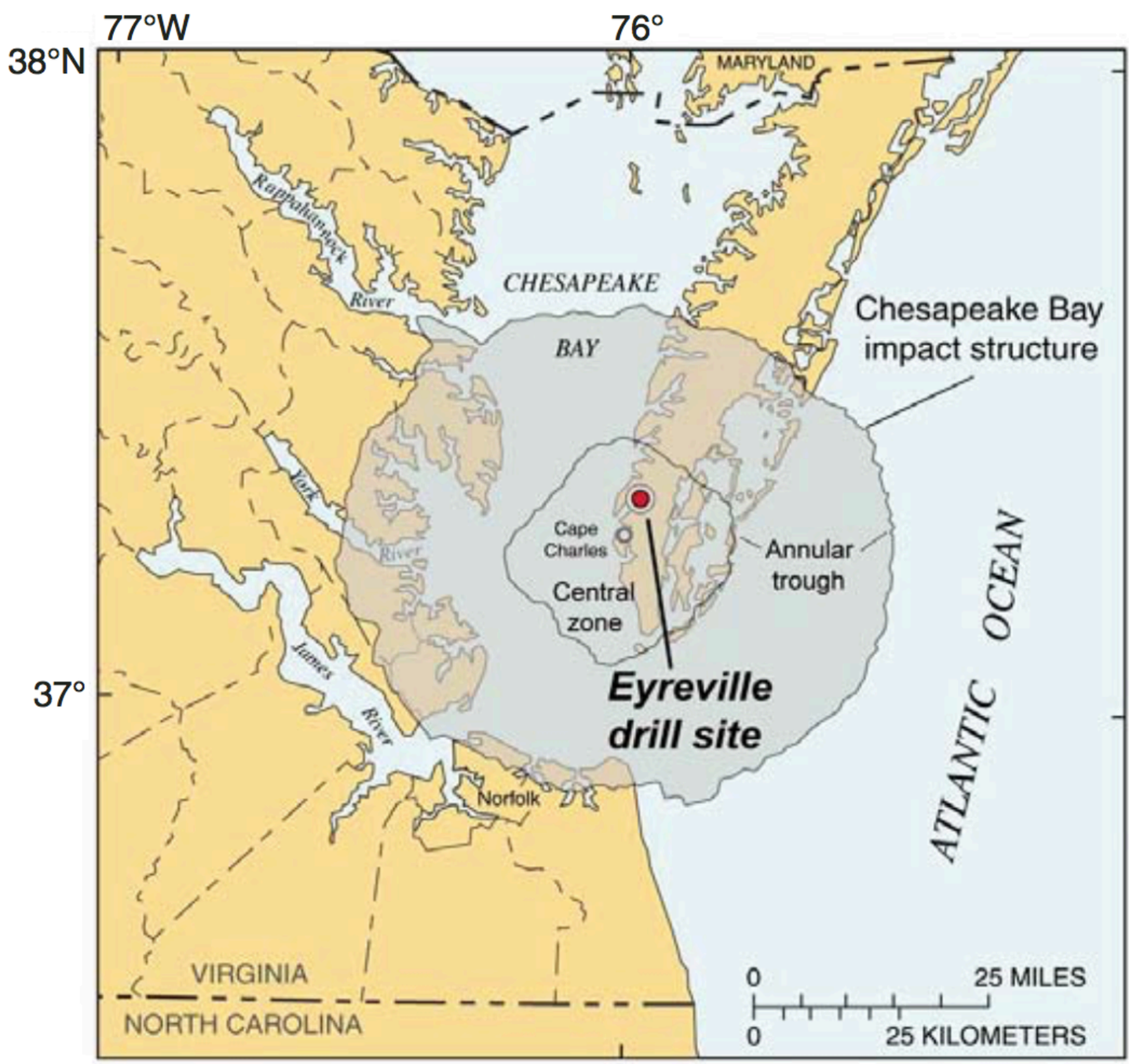
Pontefract, 2013

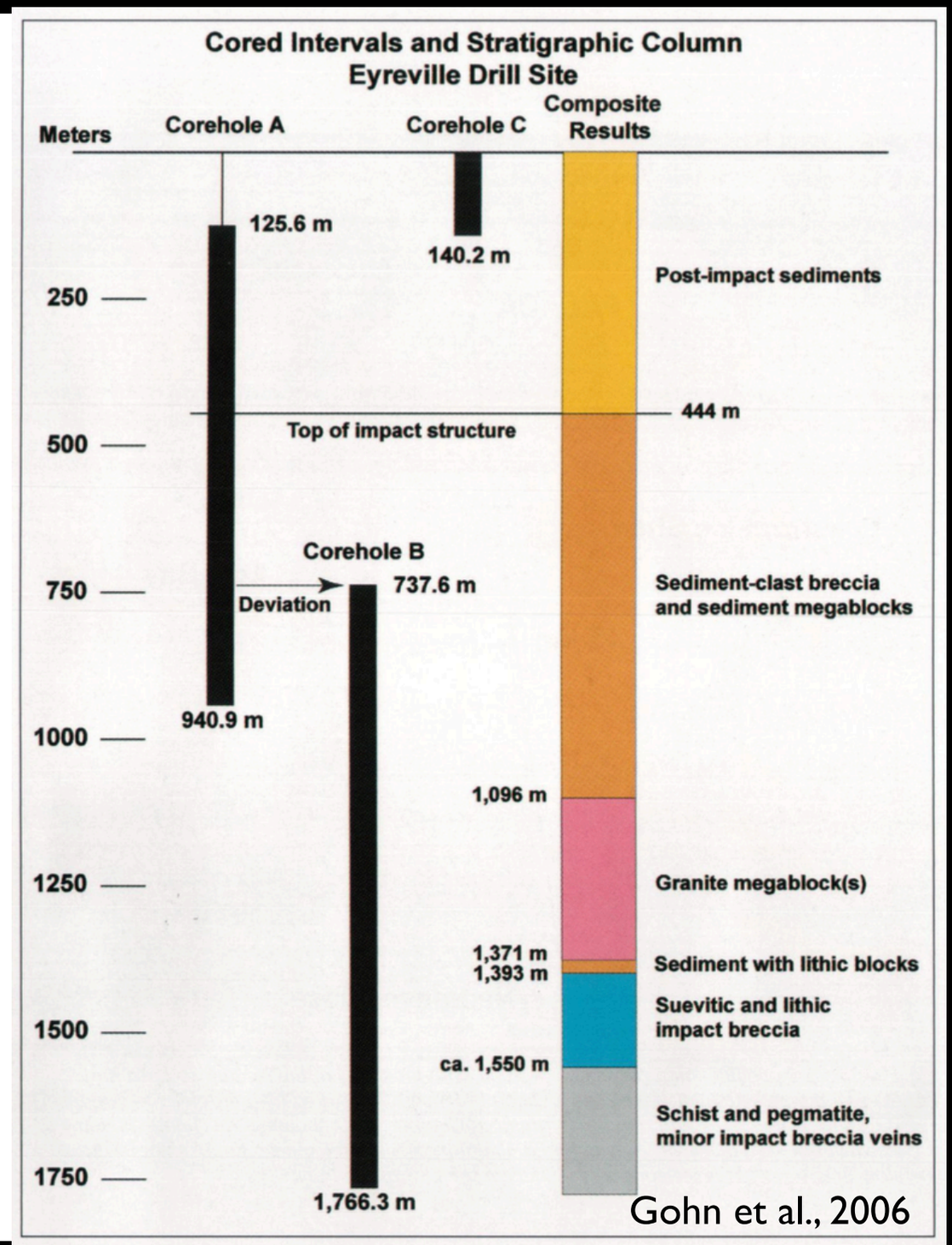


Micro-organisms isolated from shocked gneiss (left) and *in situ* colonization(right)

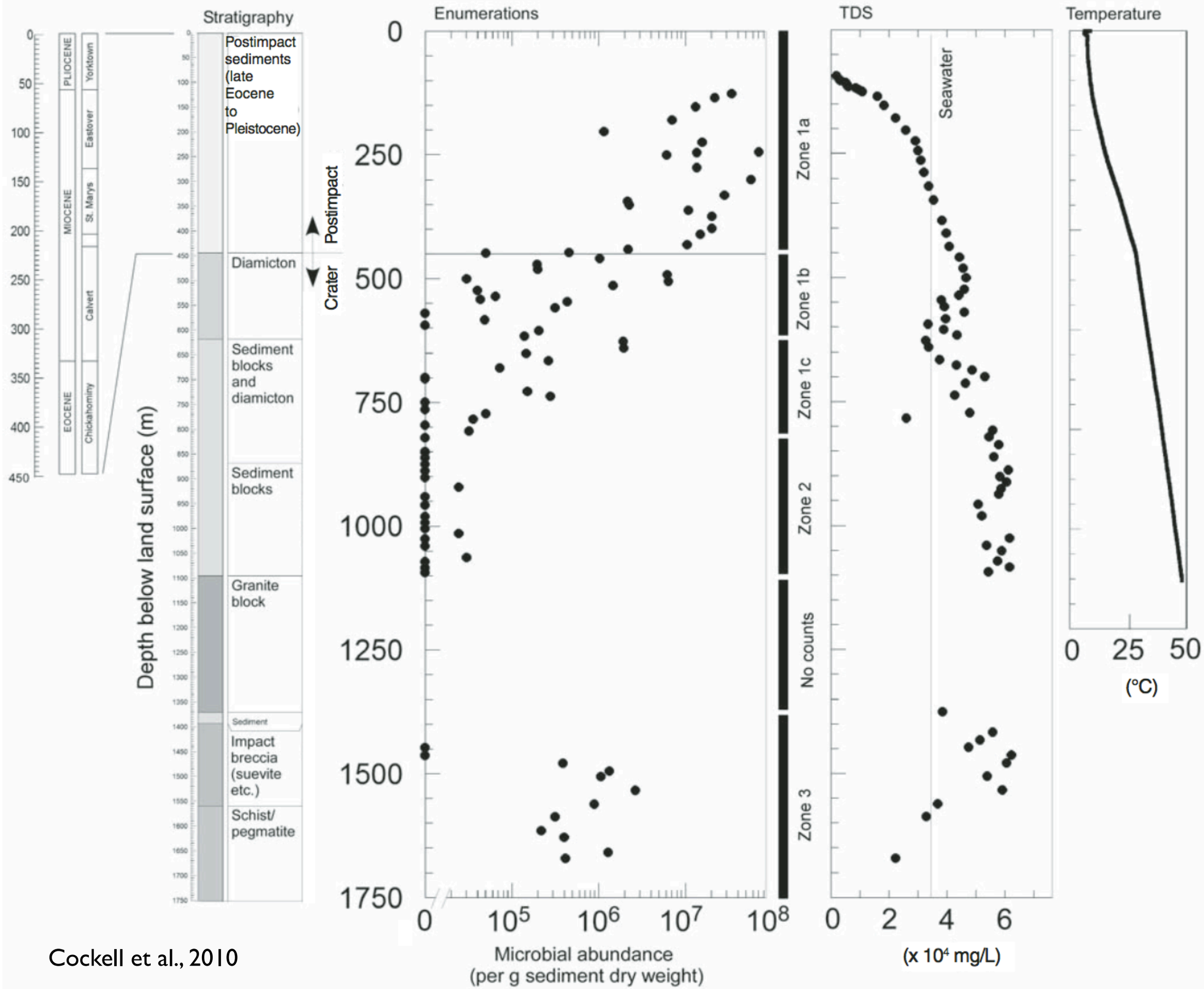
Pontefract et al., 2016

Chesapeake Bay

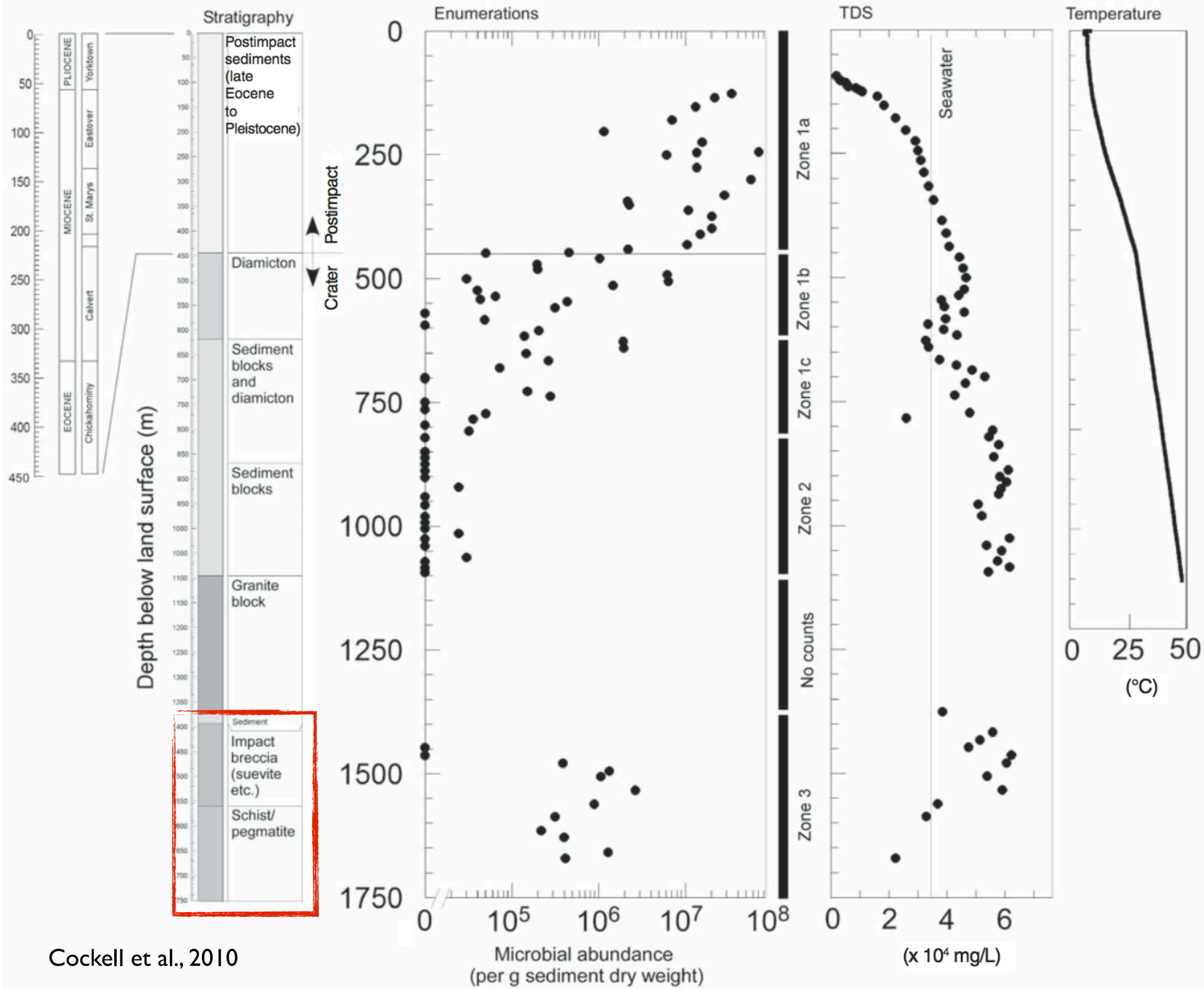




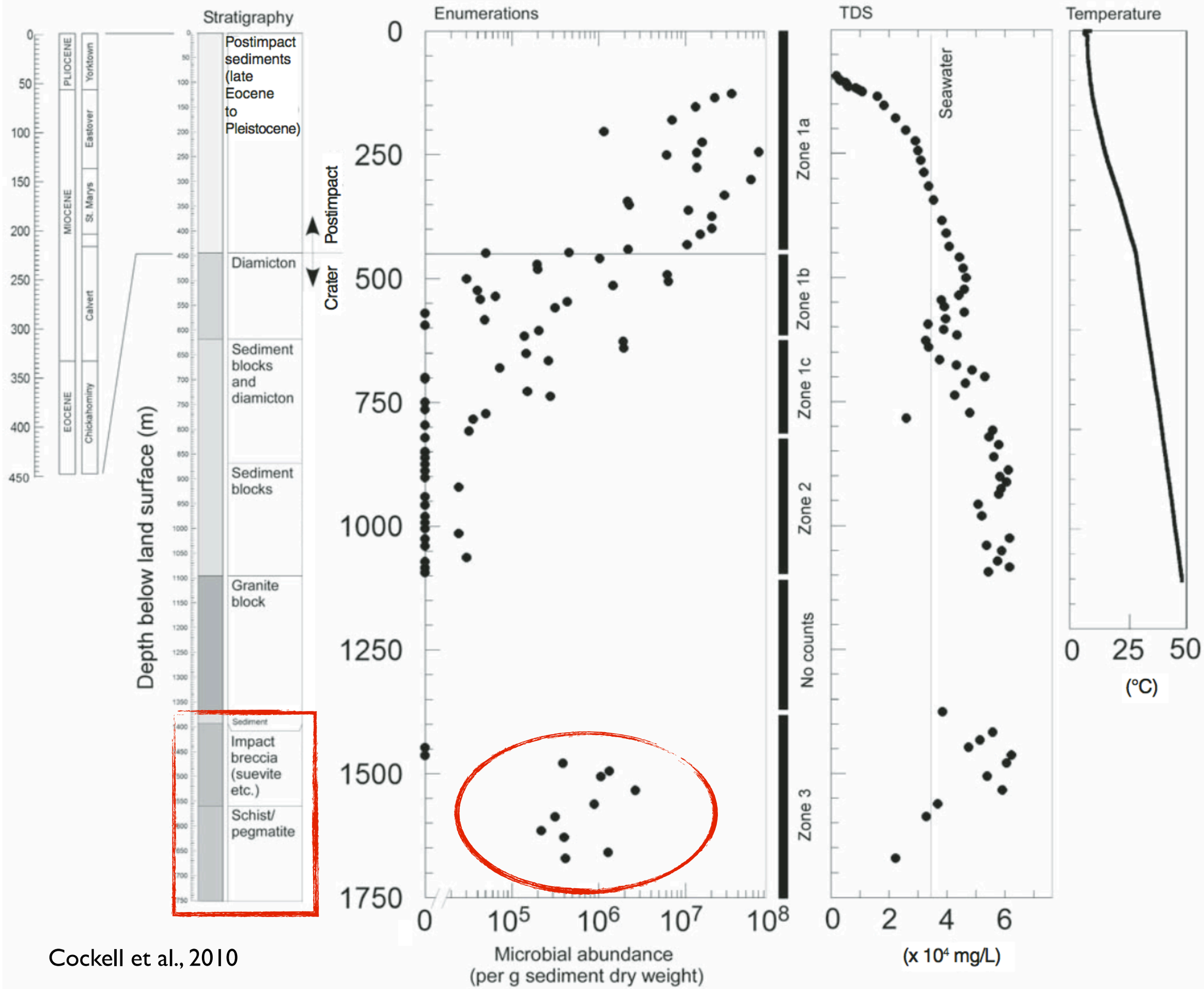
Gohn et al., 2006



Cockell et al., 2010

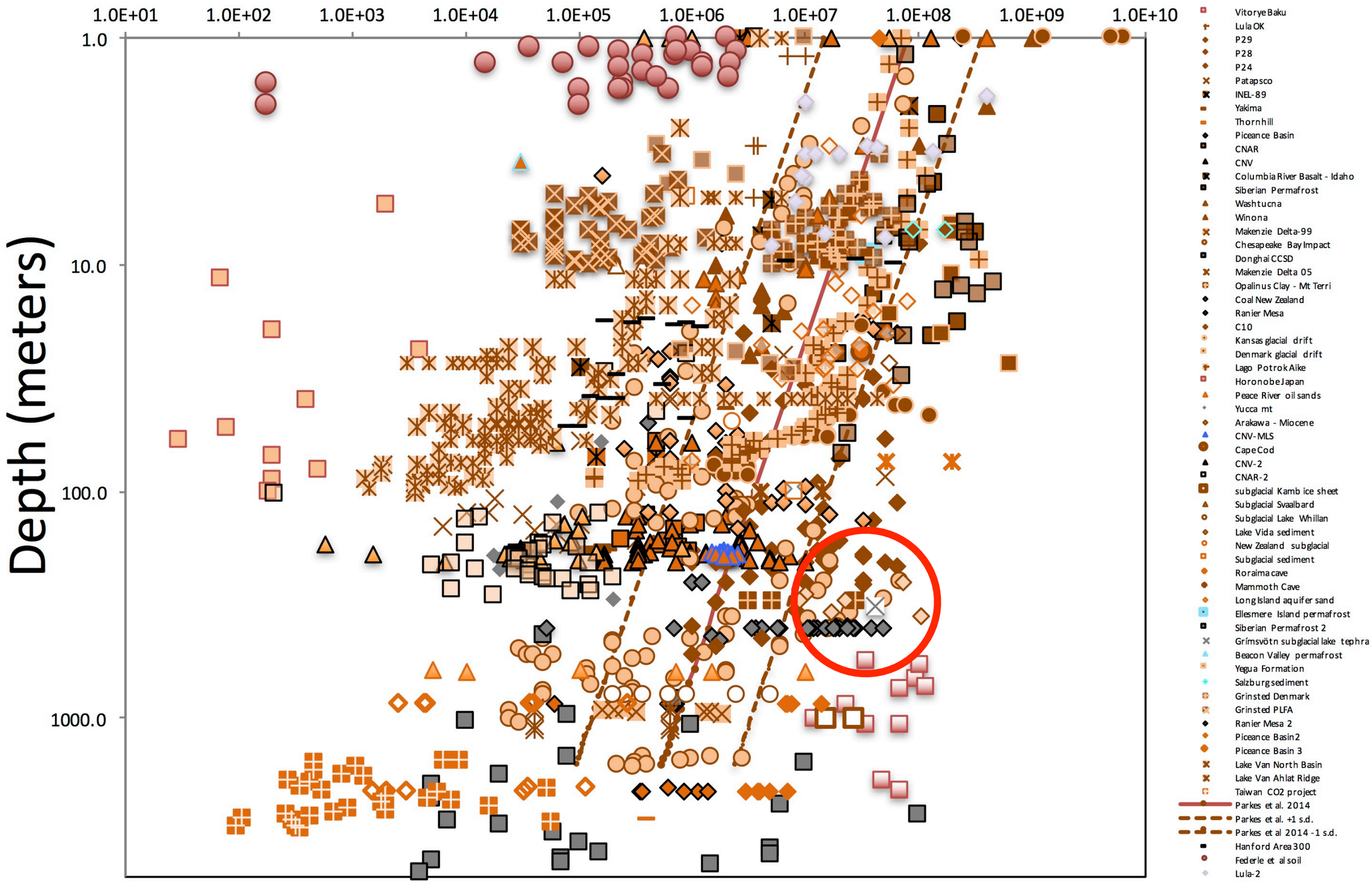


Cockell et al., 2010



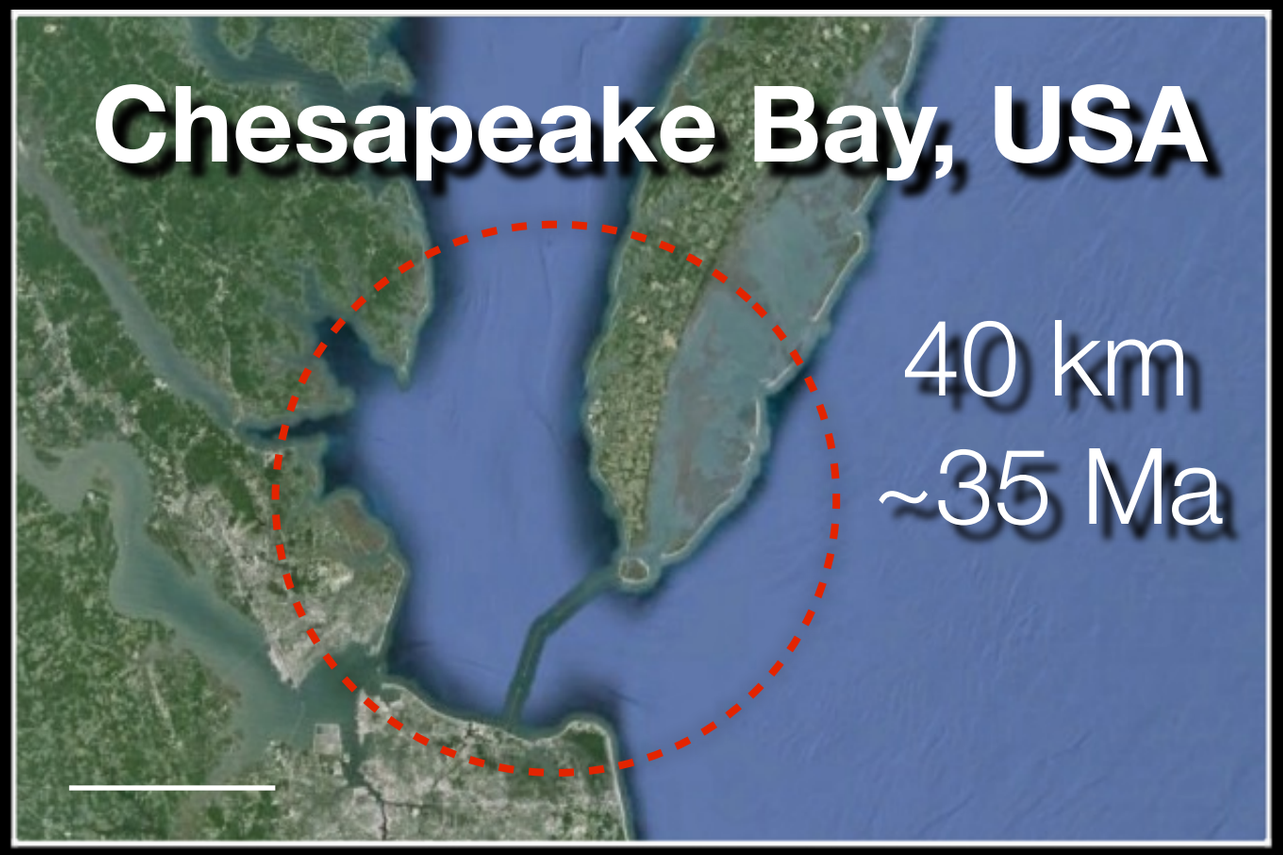
Cockell et al., 2010

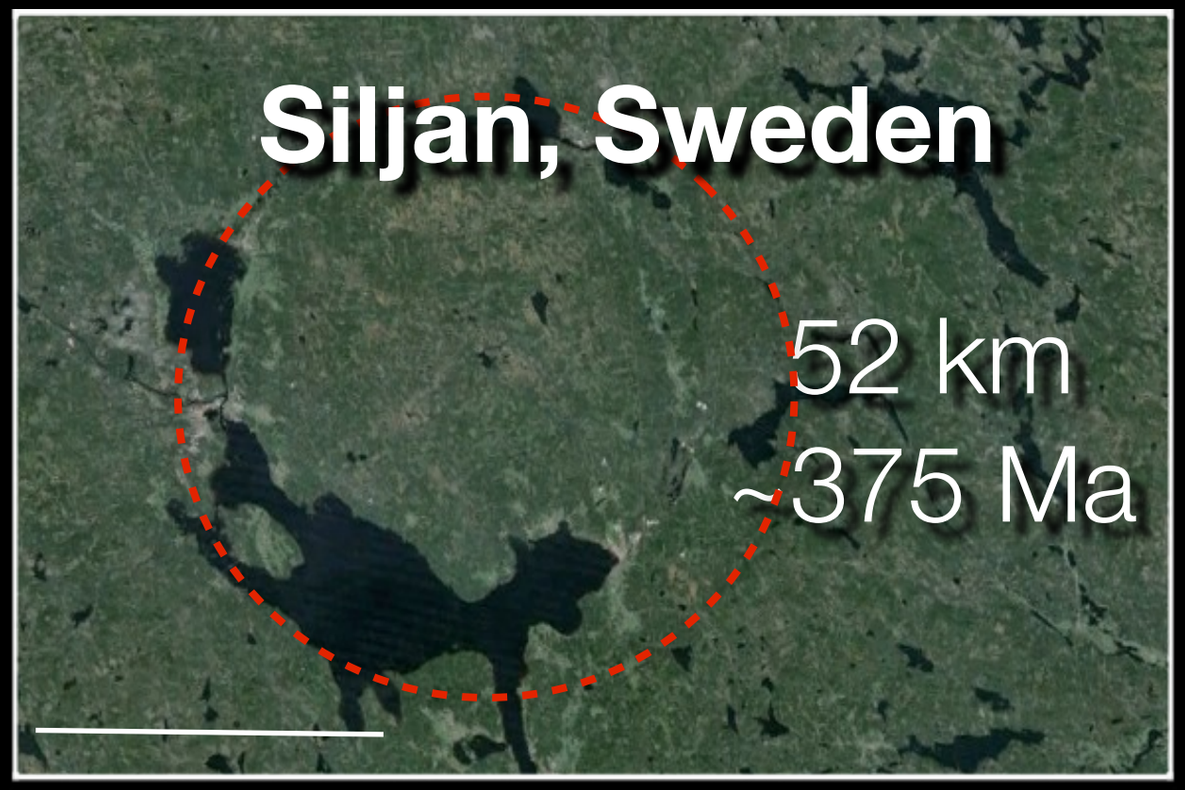
Total Biomass (cores – cells/gram)

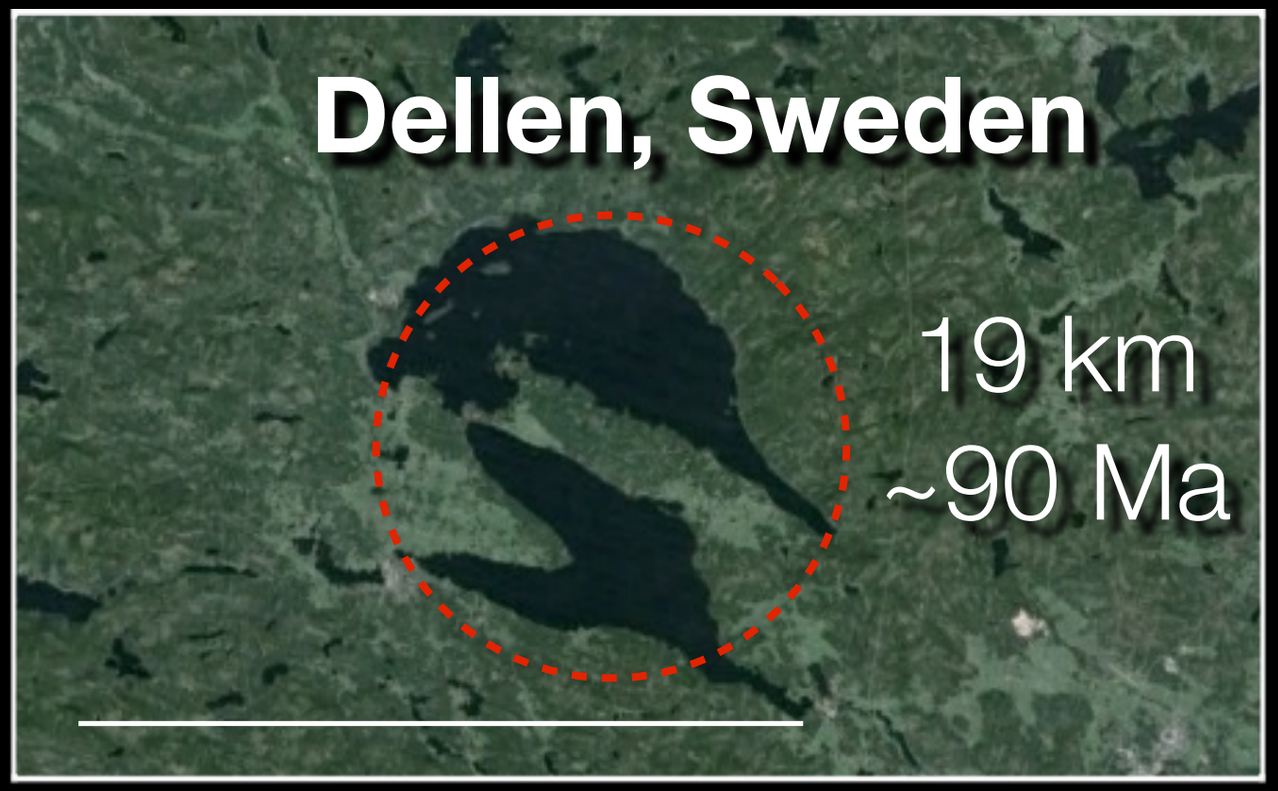


T.C. Onstott

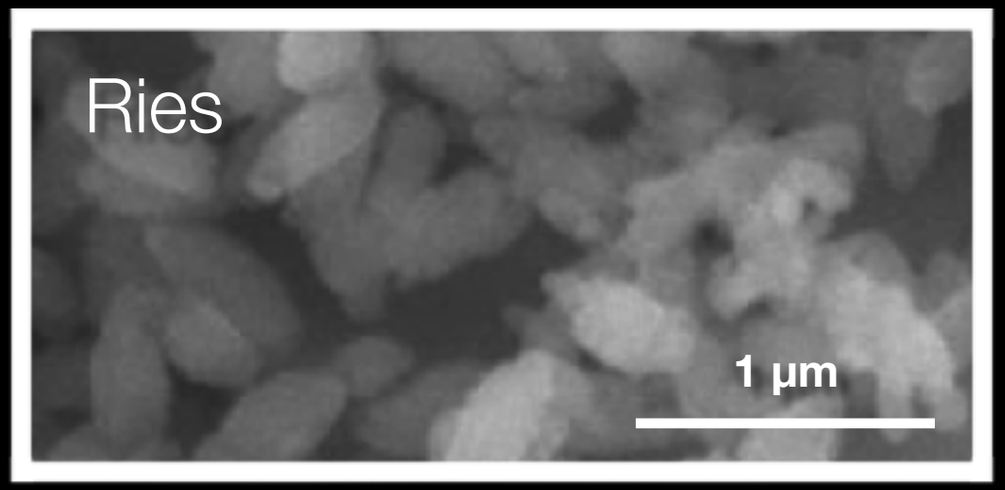
Trace fossils in impact structures



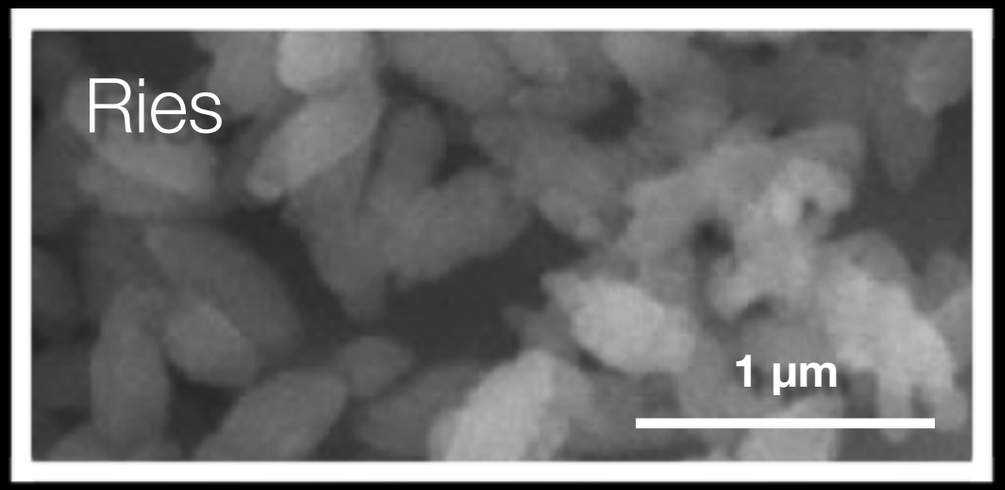




Preserved Biosignatures in Impact Generated Hydrothermal Systems



Preserved Biosignatures in Impact Generated Hydrothermal Systems



- **Ries** Glamoclija *et al;* **Cheasapeake Bay** Glamoclija *et al.*
    - features of potential morphological interest

Preserved Biosignatures in Impact Generated Hydrothermal Systems

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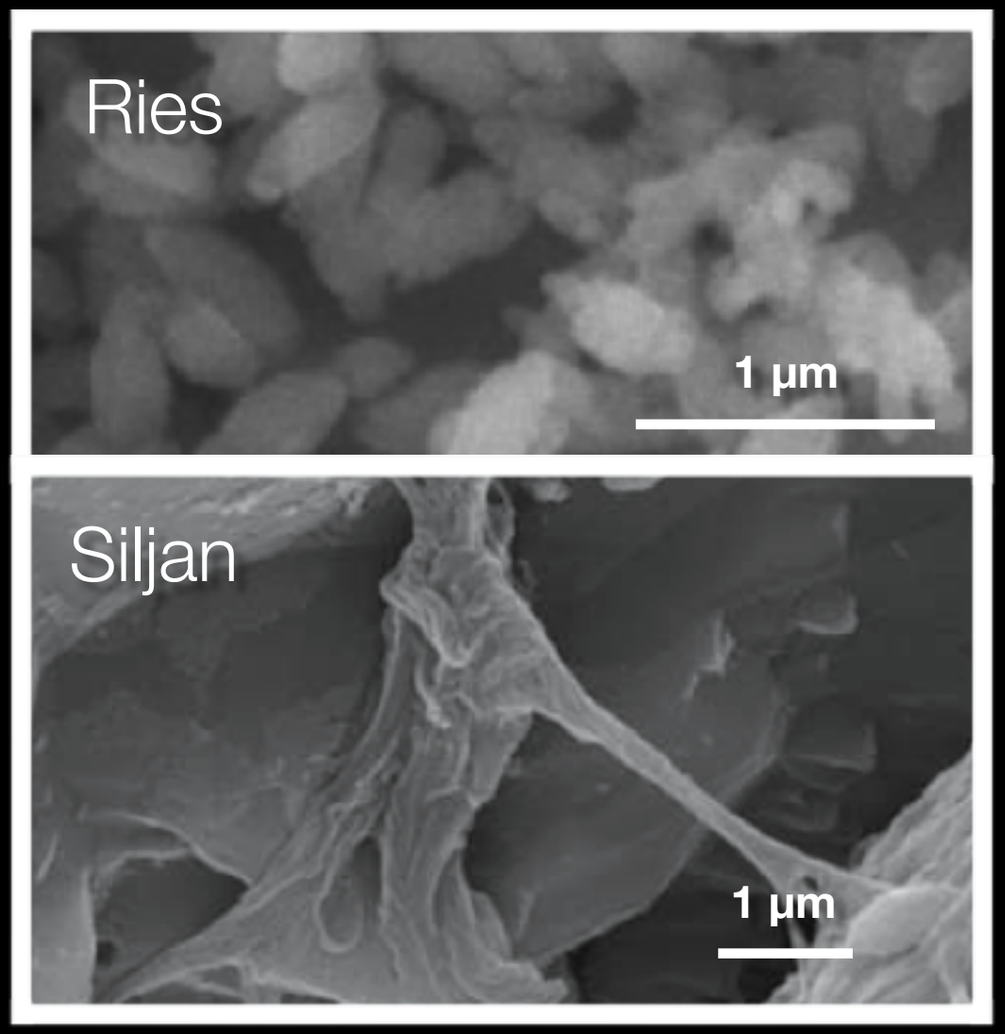
  - evidence for EPS in hydrothermal veins



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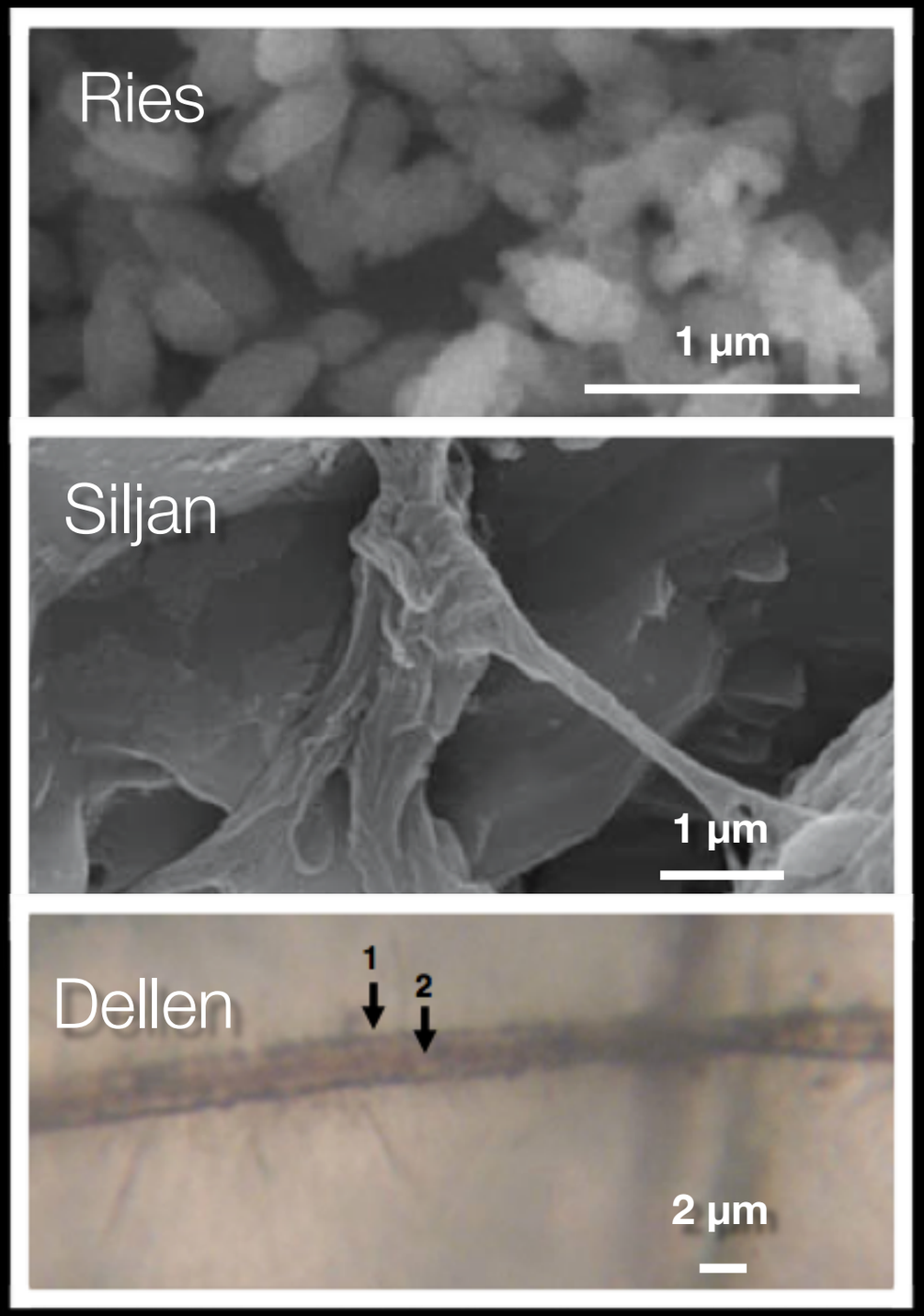

Preserved Biosignatures in Impact Generated Hydrothermal Systems

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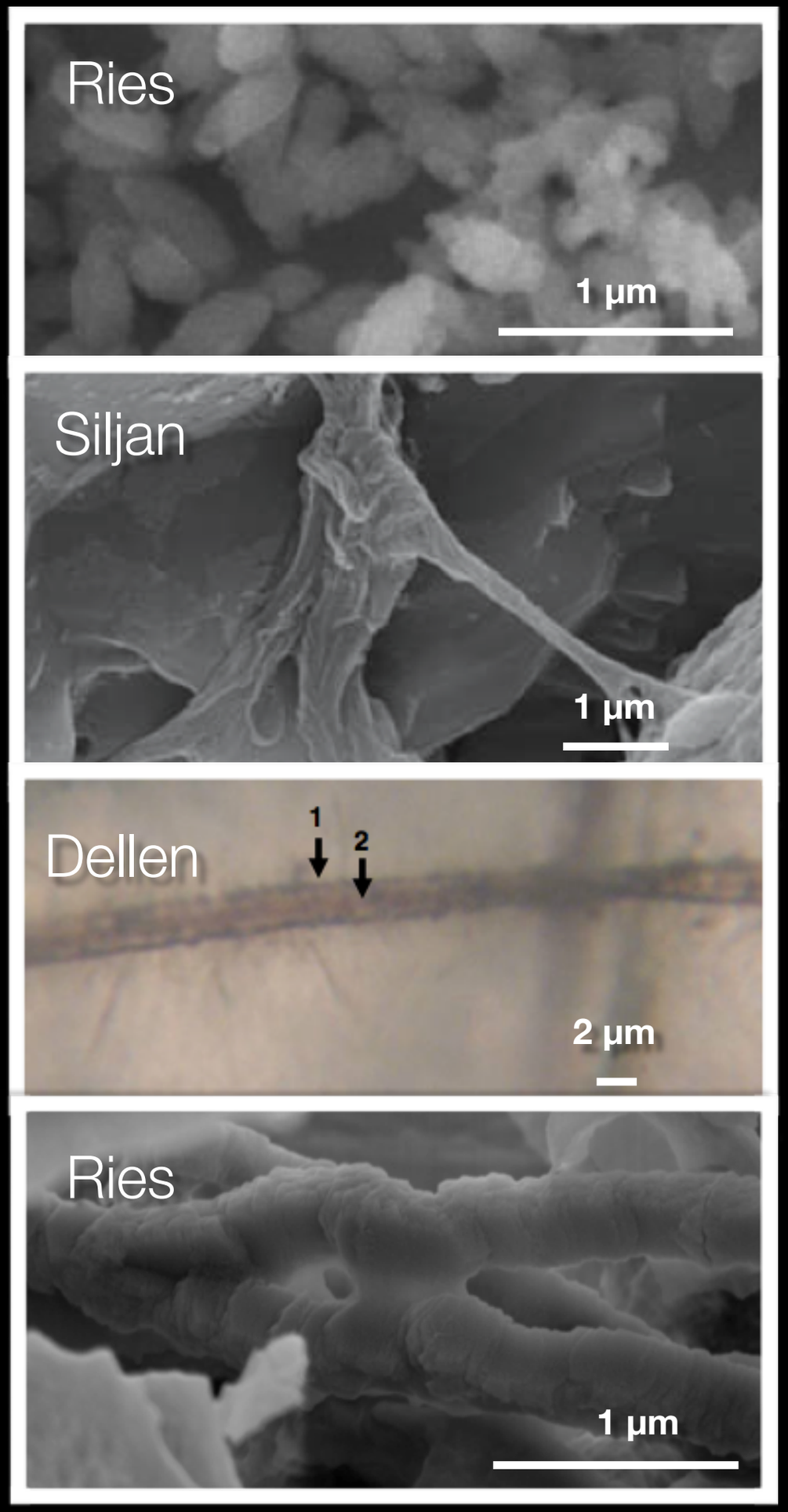
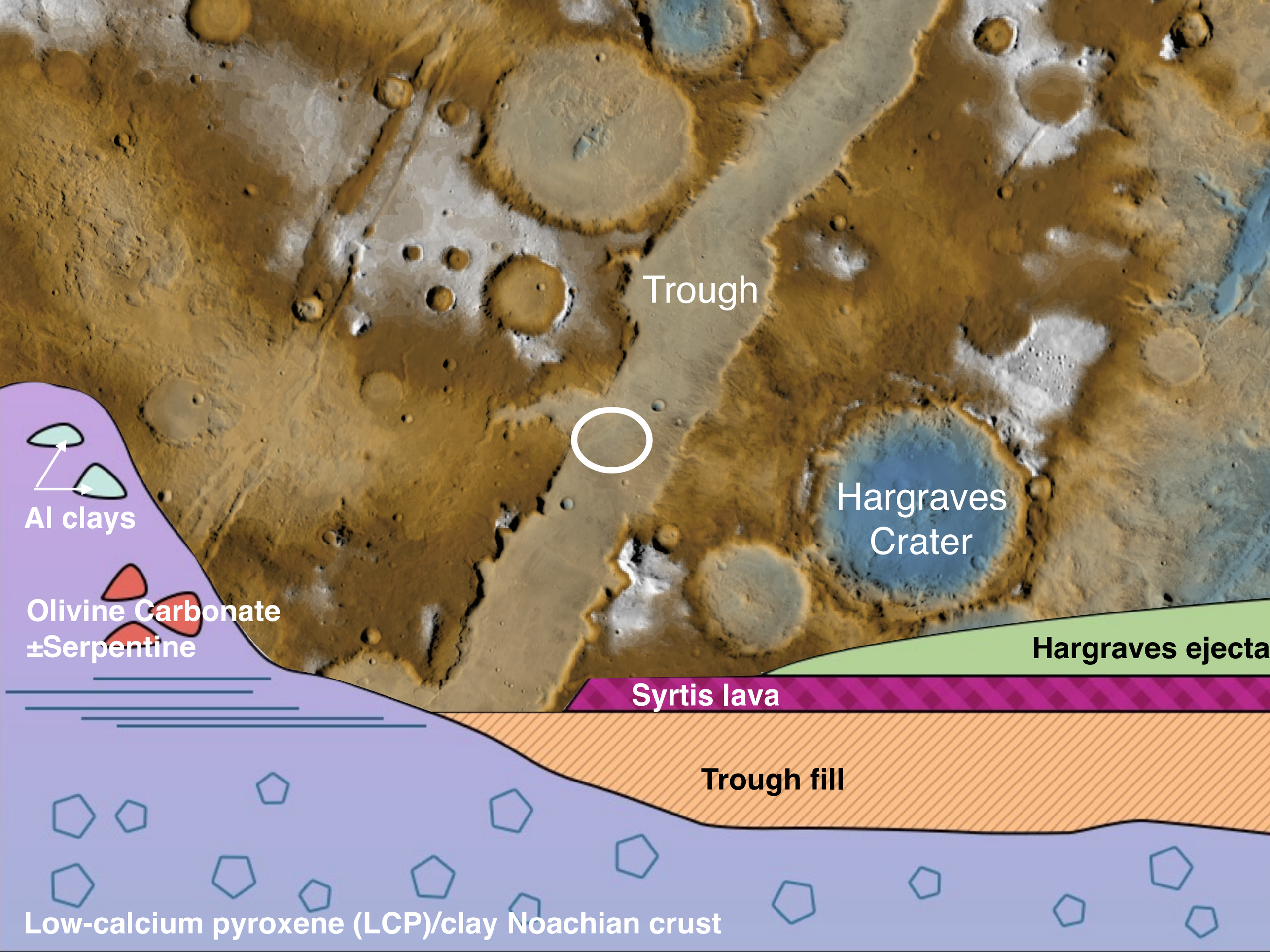
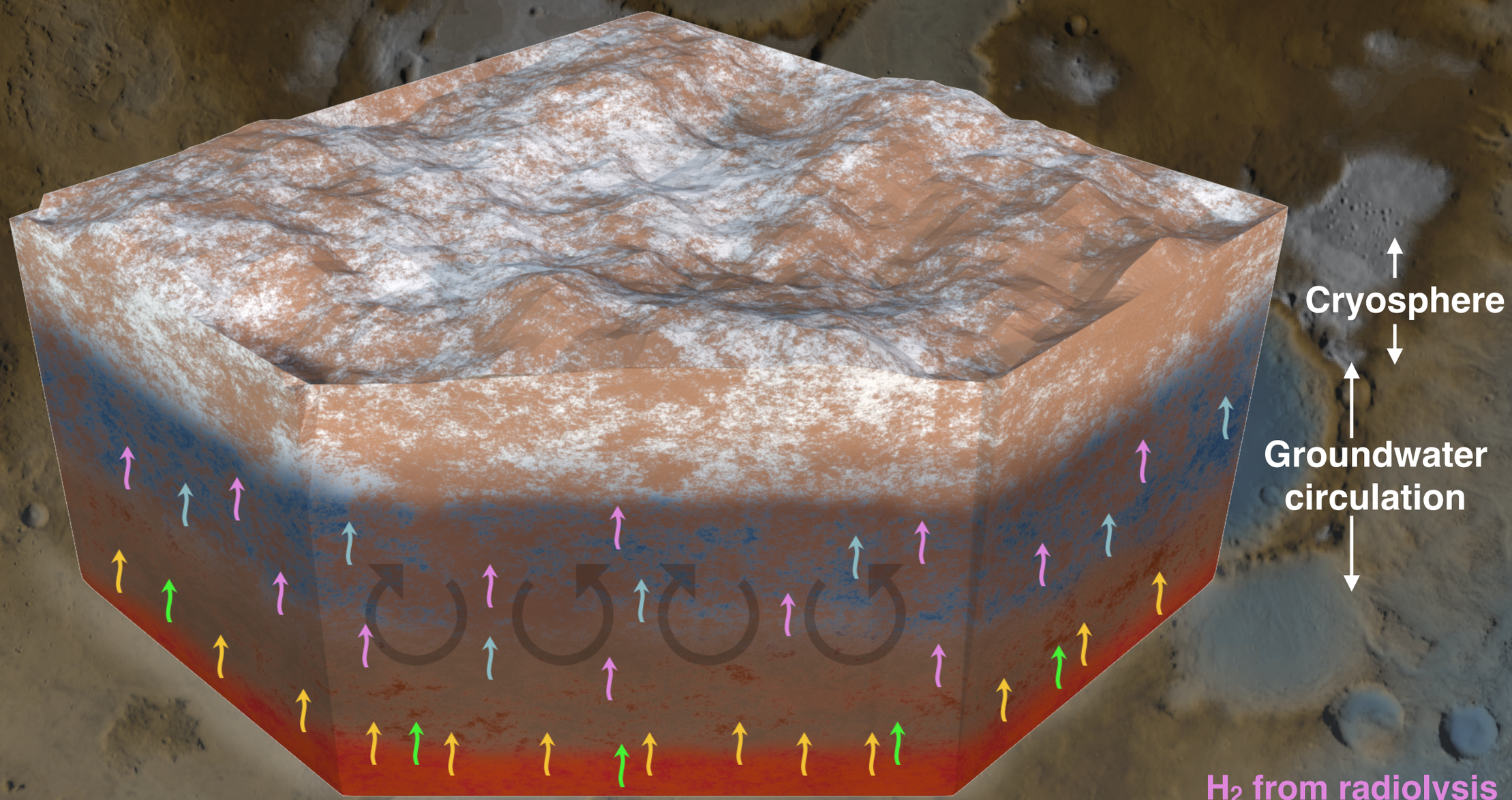
- **Dellen** Lindgren *et al*
  - features of potential morphological interest
- **Ries** Sapers *et al*
  - evidence for filamentous ichnofossils in impact glass



Trough
Hargraves
Crater
Syrtis
lavas
20 km


Trough
Hargraves
Crater
Al clays
Olivine Carbonate
±Serpentine
Hargraves ejecta
Syrtis lava
Trough fill
Low-calcium pyroxene (LCP)/clay Noachian crust

Rock-hosted life habitat



- Mustard & Tarnas 2017 (LPSC)

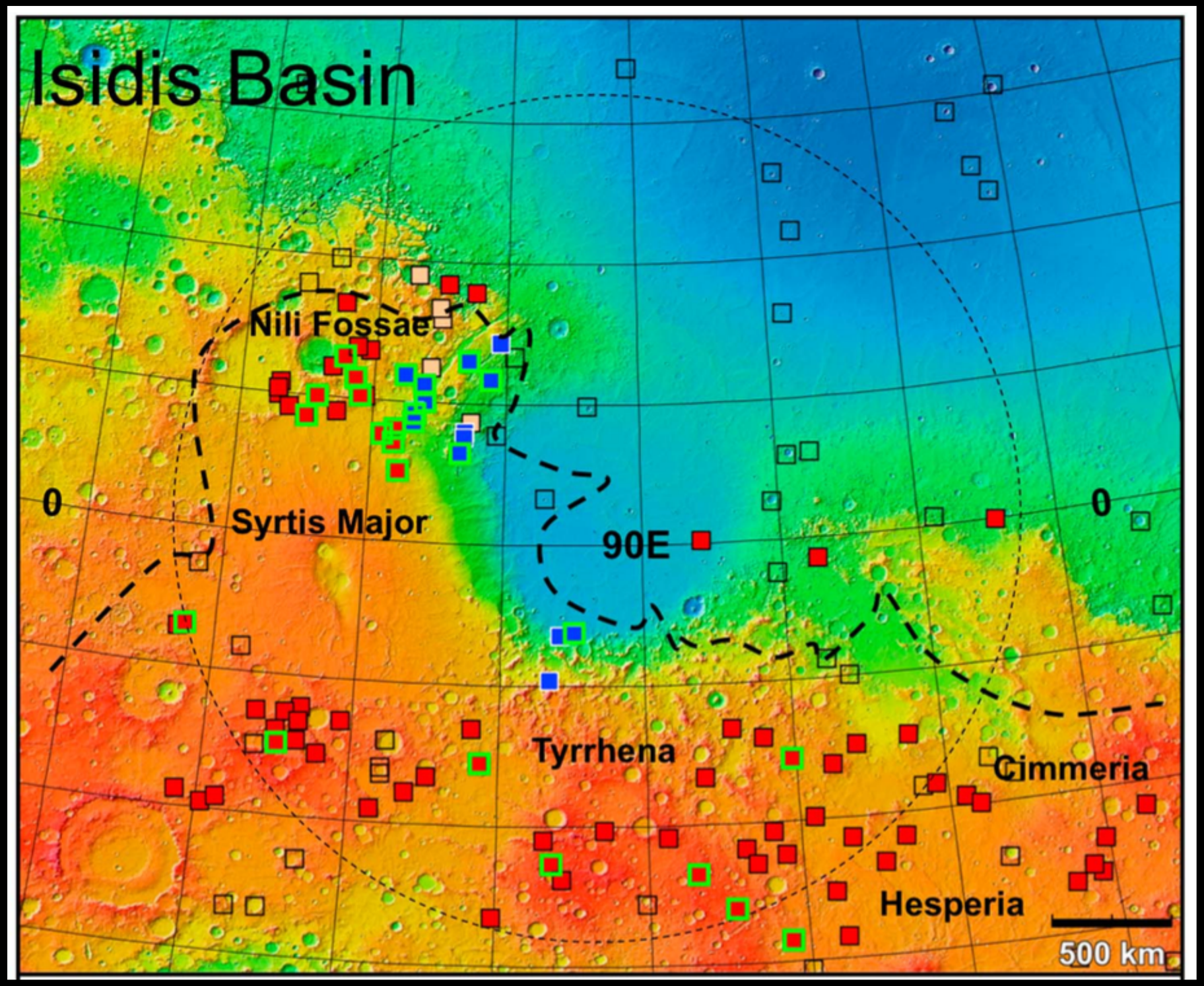
H_2 from radiolysis

H_2 from low-T serpentinization

H_2 from high-T serpentinization

CH_4 from high-T serpentinization

Hydrated Silicates Associated with Megabreccias



mega-breccia

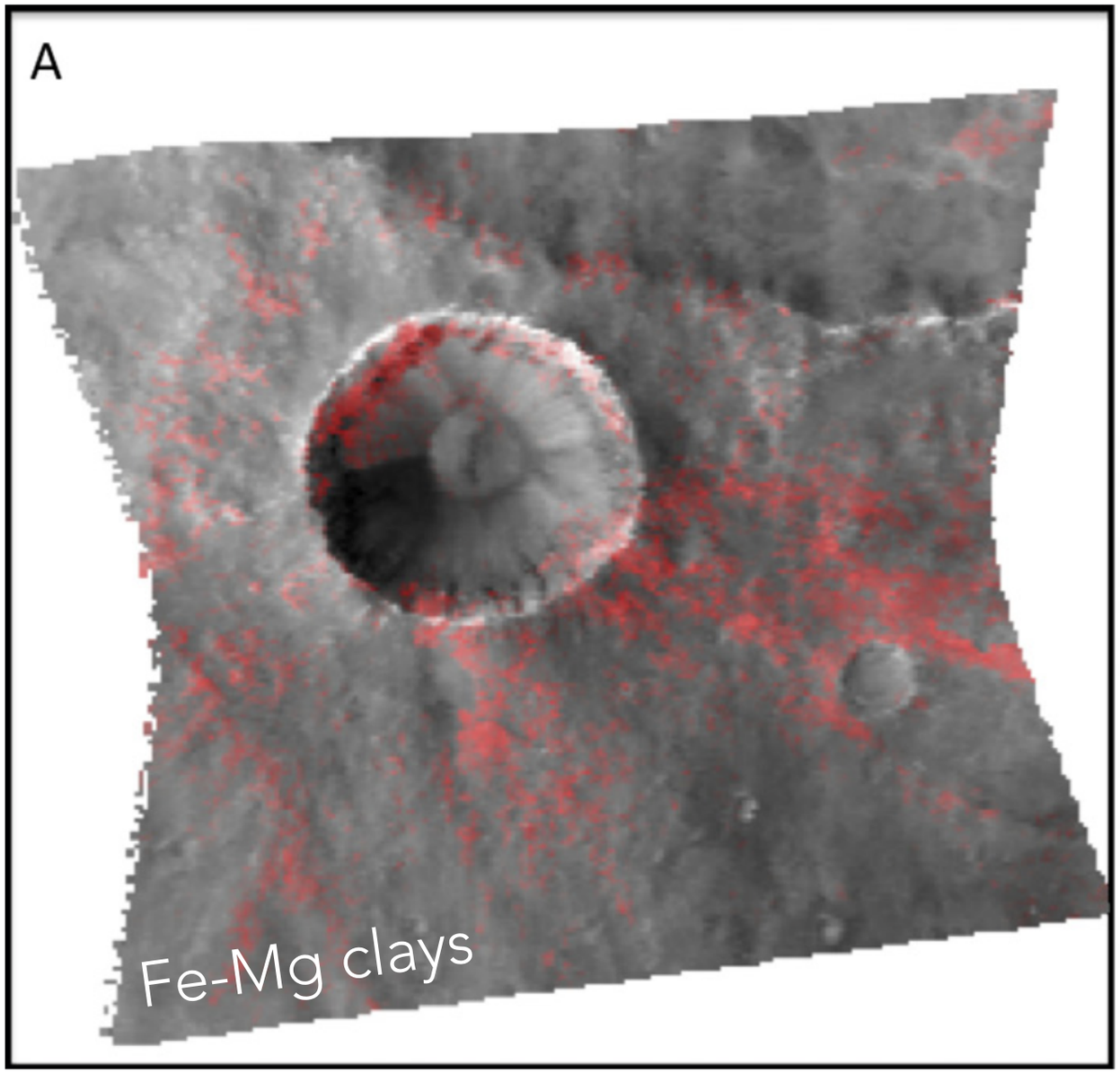
hydrated silicates ('crustal')

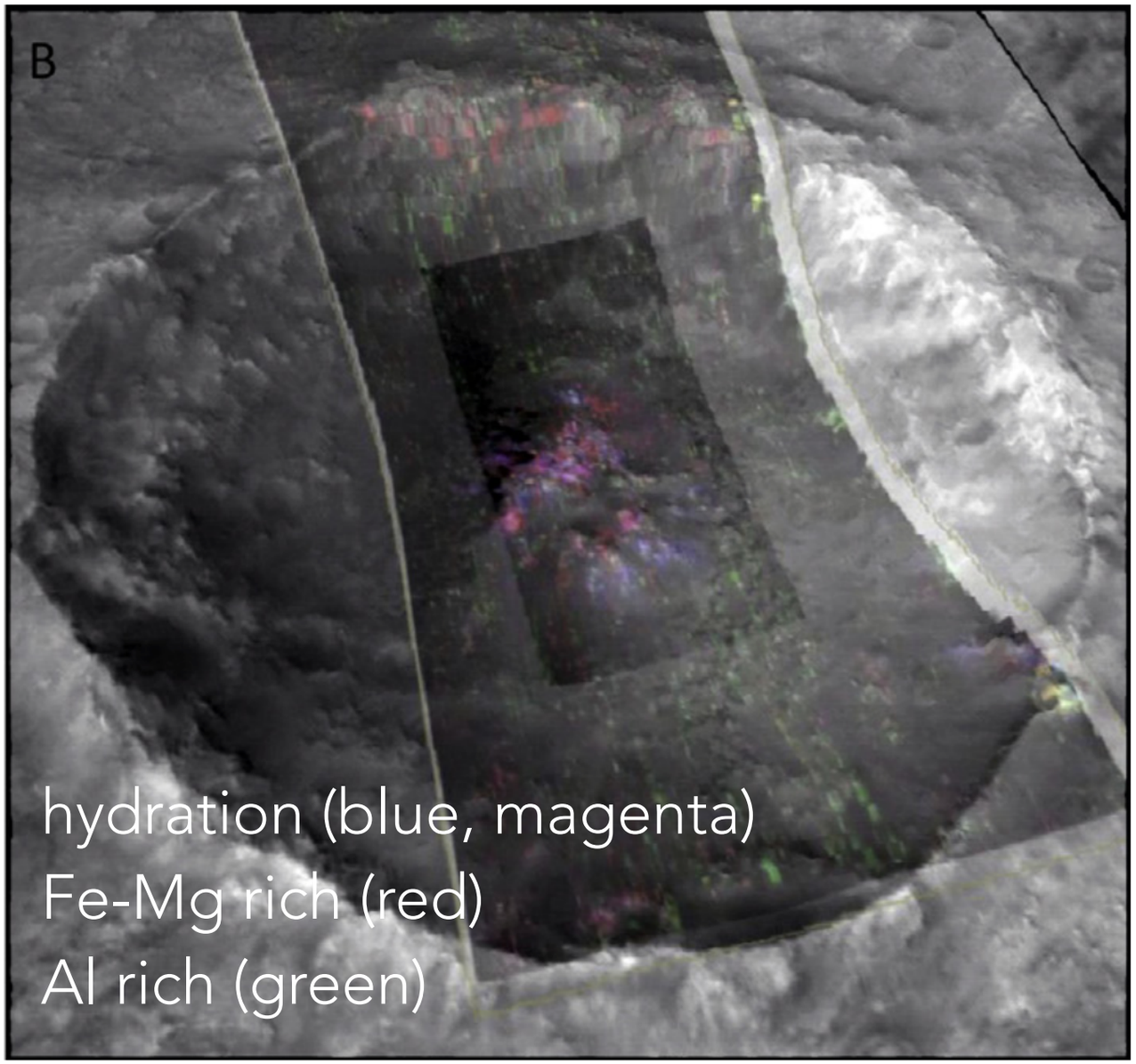
hydrated silicates ('stratigraphic')

Tornabene et al 2013

Impact Hydrothermal Systems on Mars

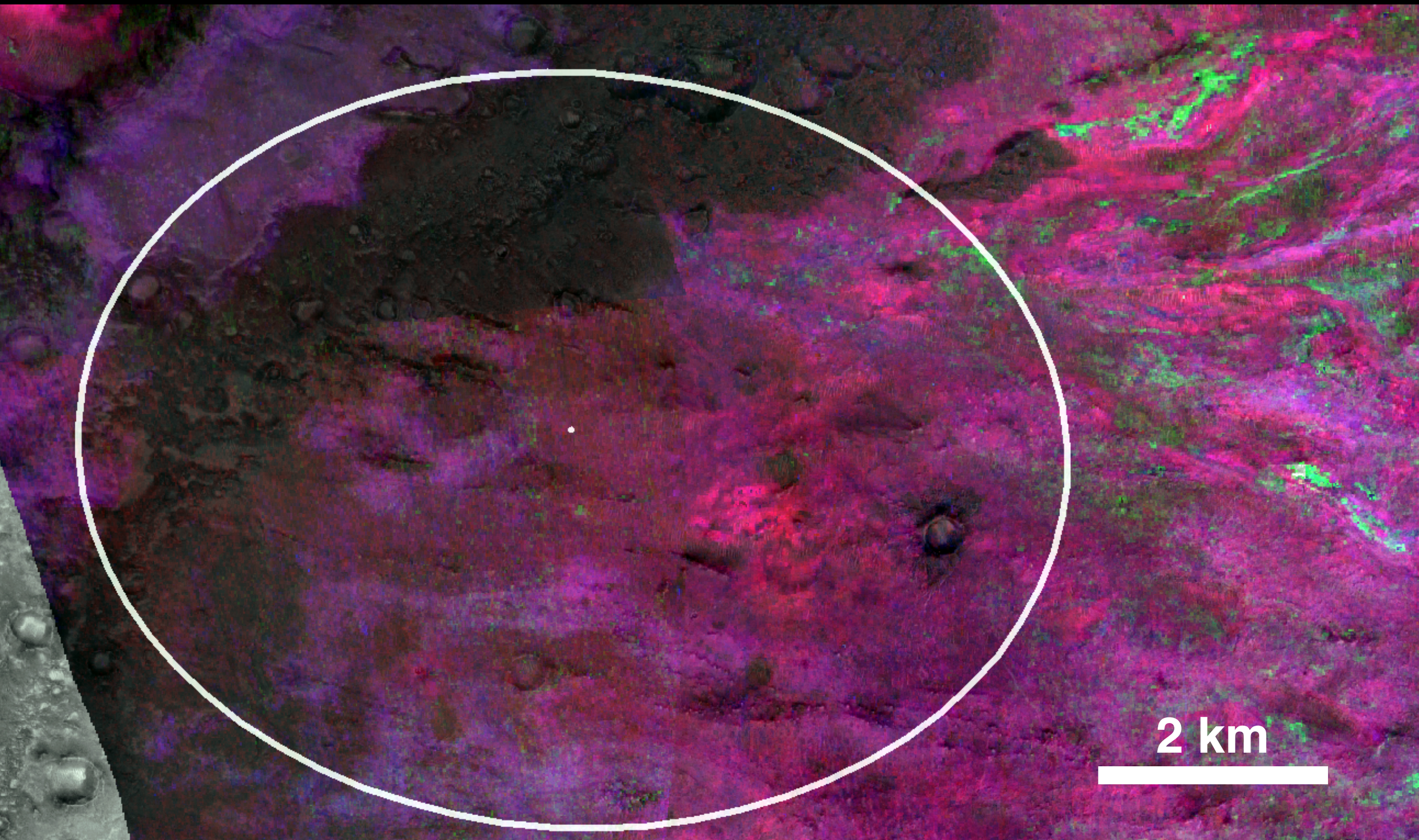
- phyllosilicate deposits: post-, syn-, or pre-impact?
- **excavation and hydrothermal**



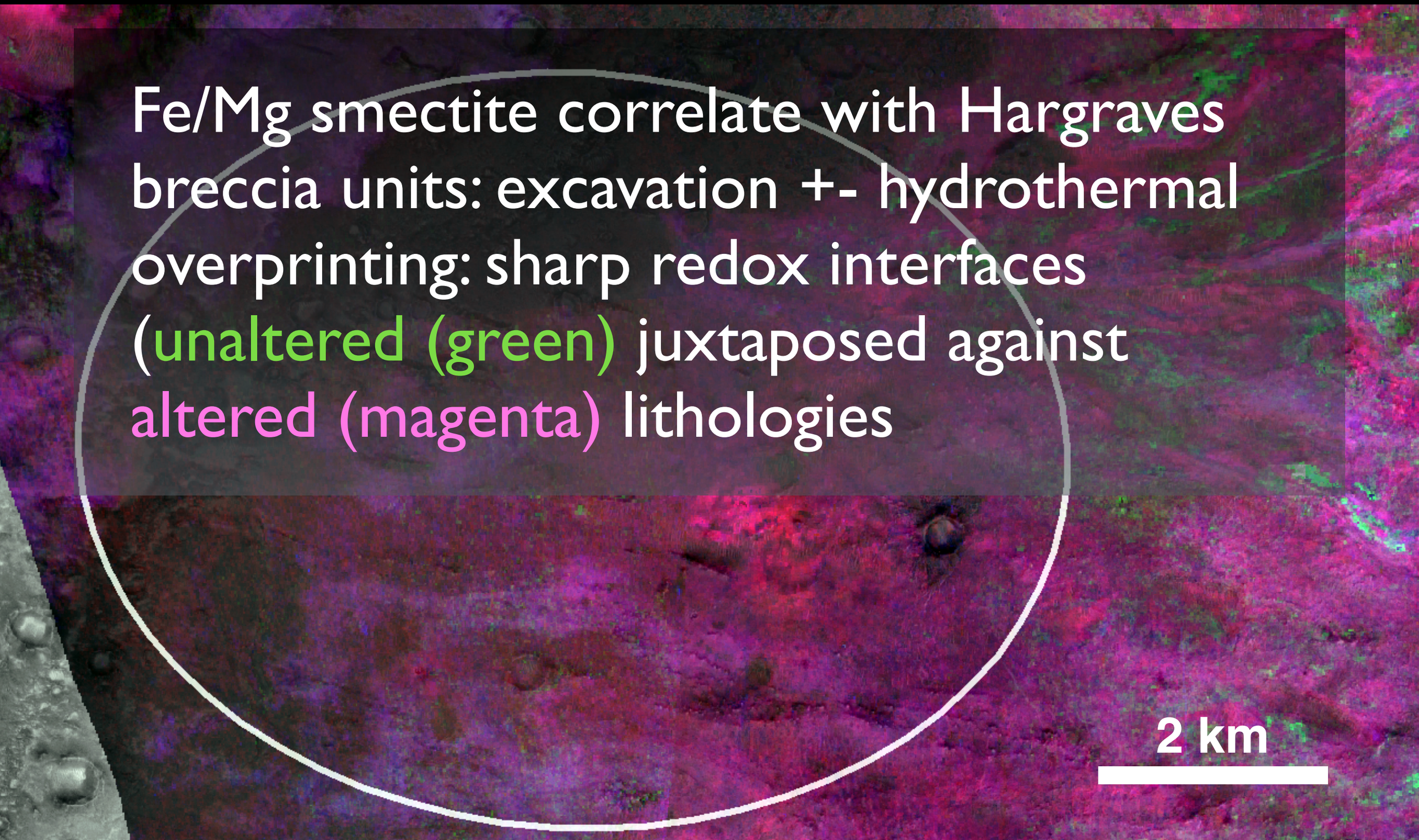


Osinski et al 2013

Phyllosilicate exposures

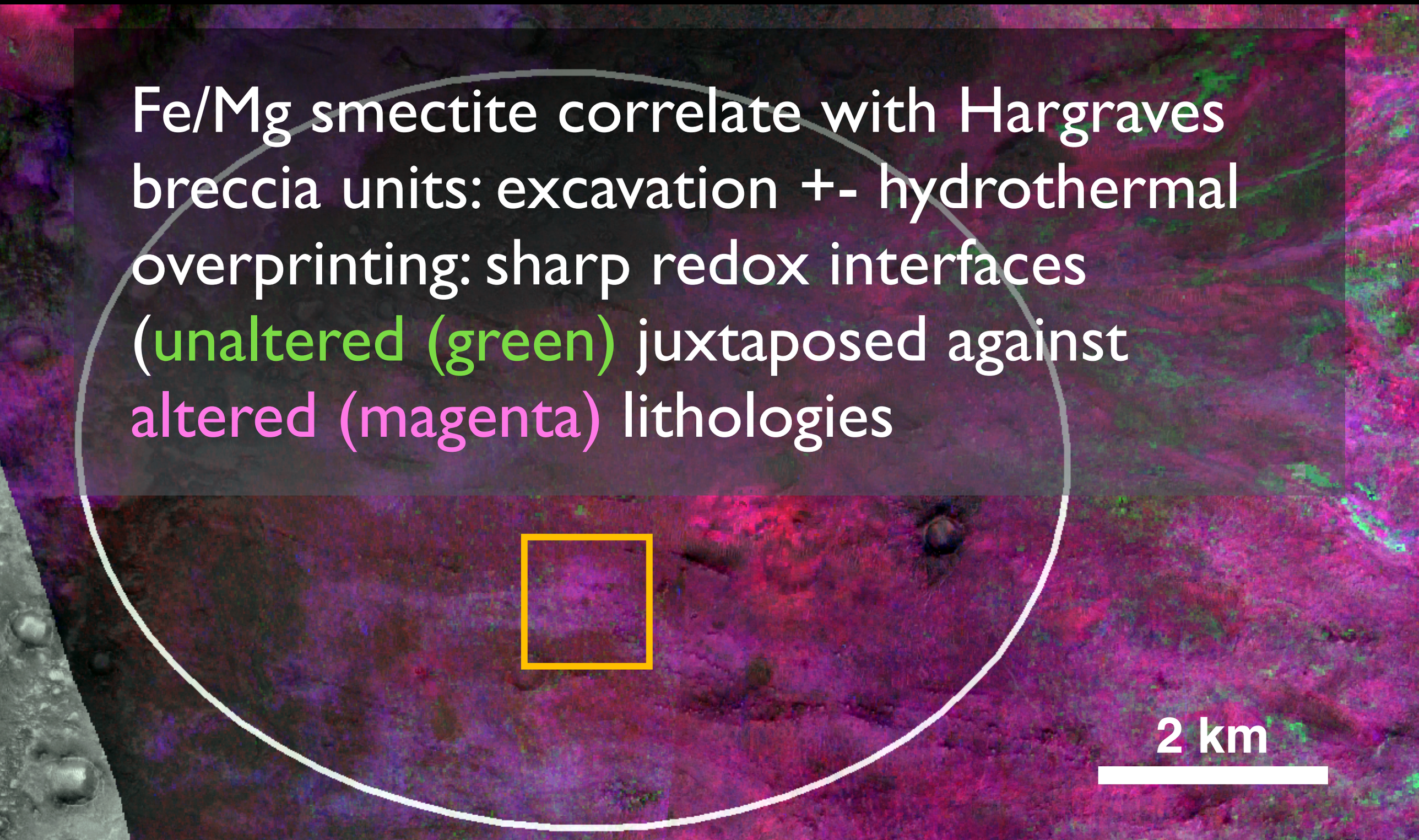


Phyllosilicate exposures



Fe/Mg smectite correlate with Hargraves breccia units: excavation +- hydrothermal overprinting: sharp redox interfaces (unaltered (green) juxtaposed against altered (magenta) lithologies

Phyllosilicate exposures



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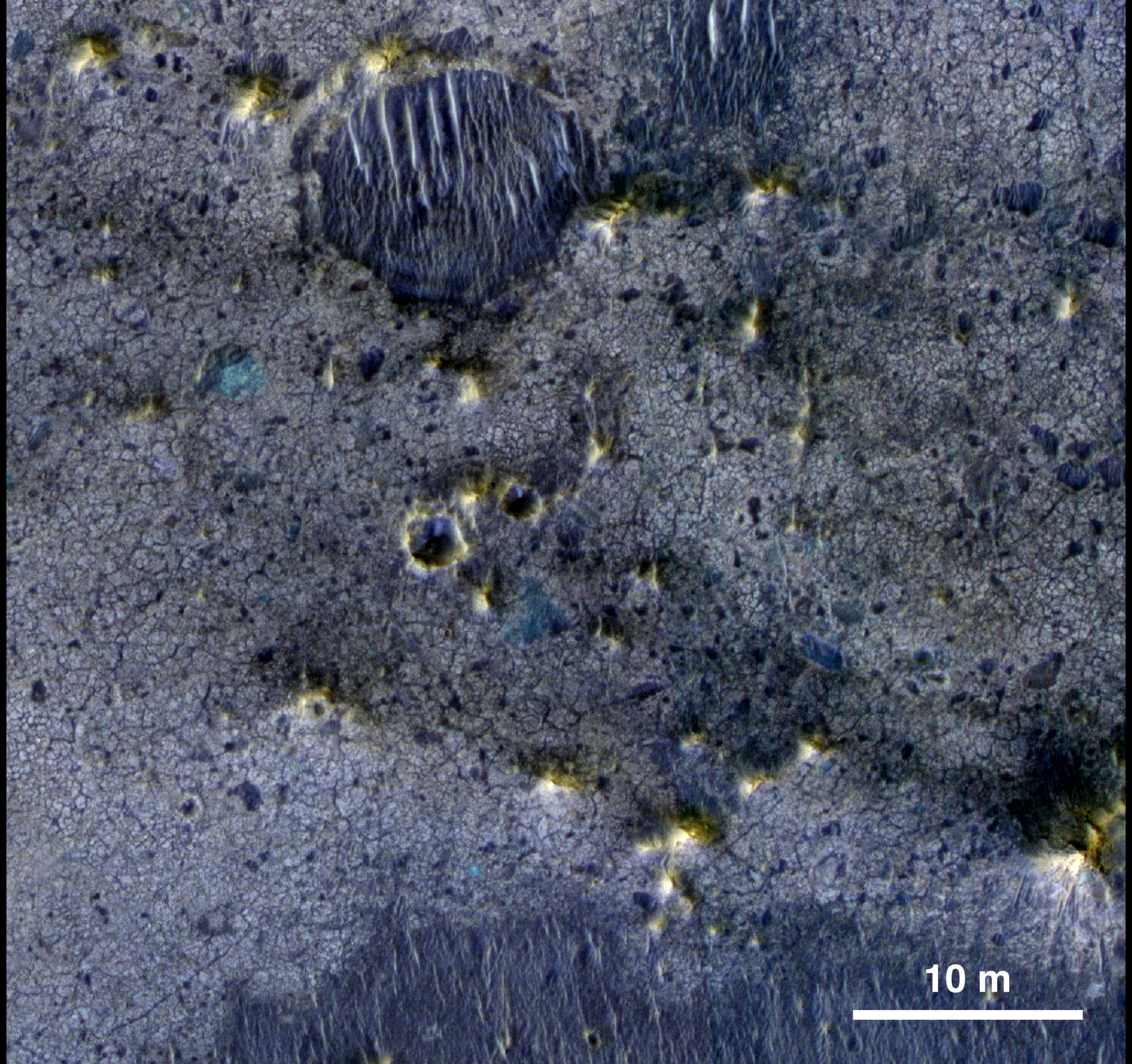
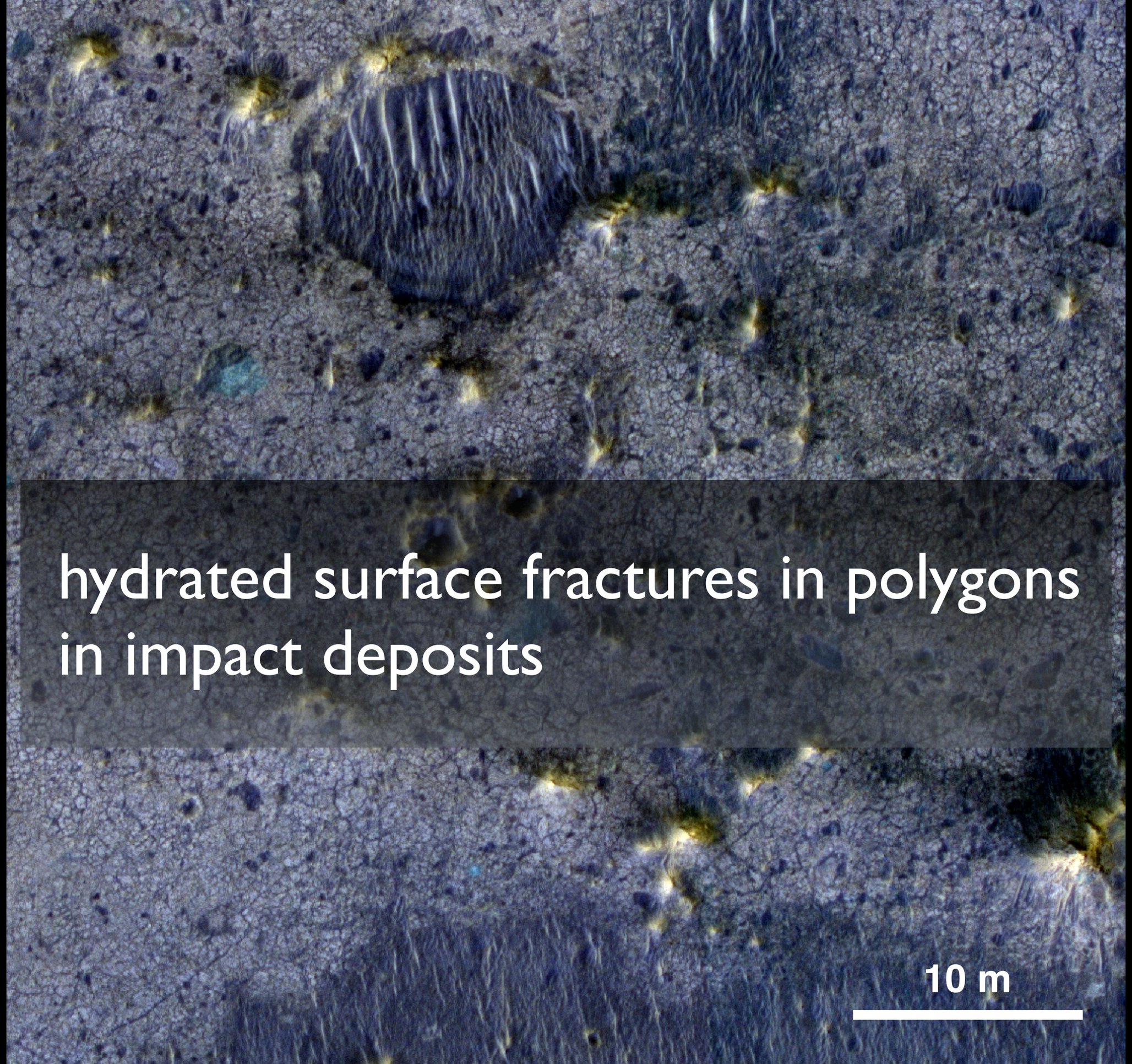
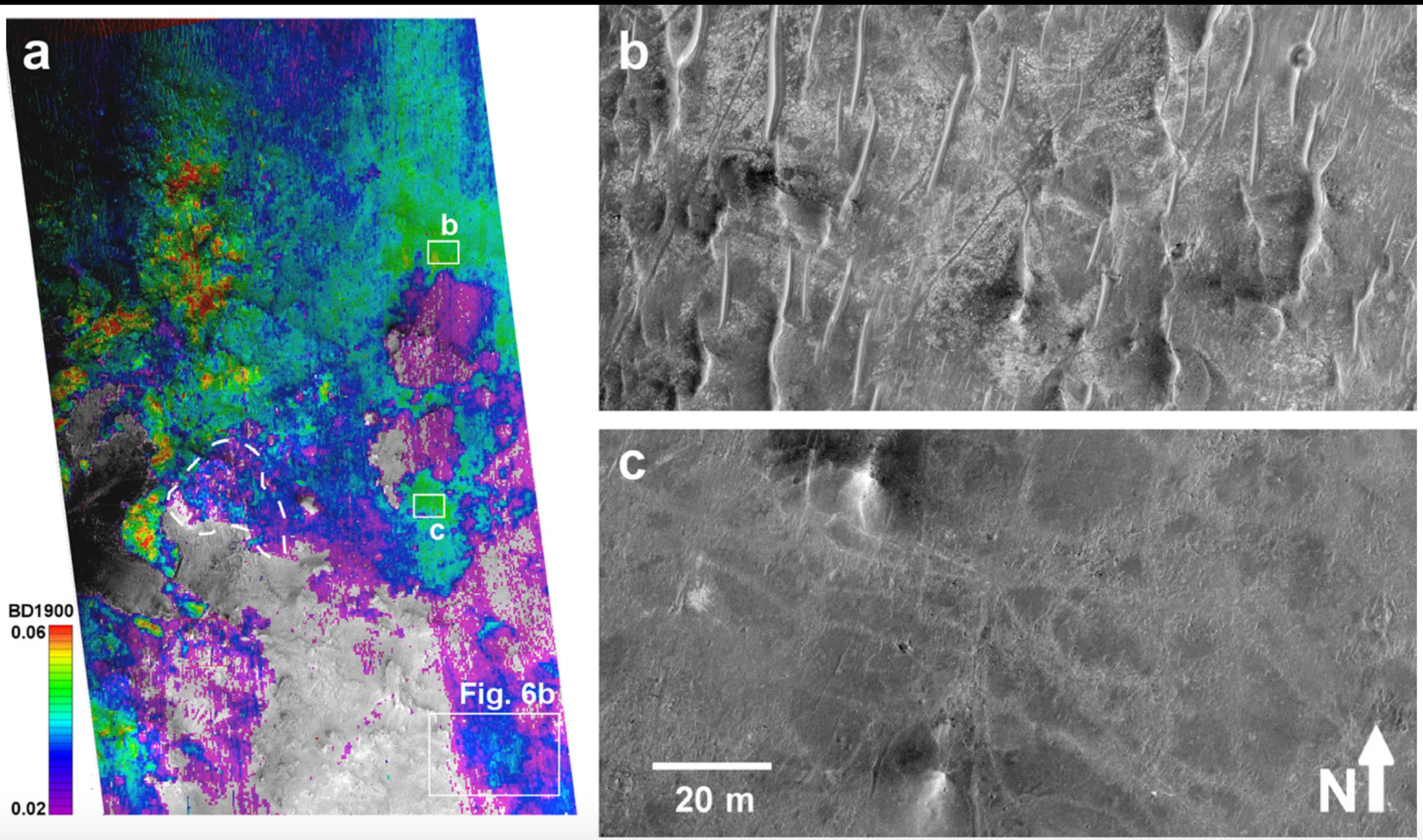

10 m



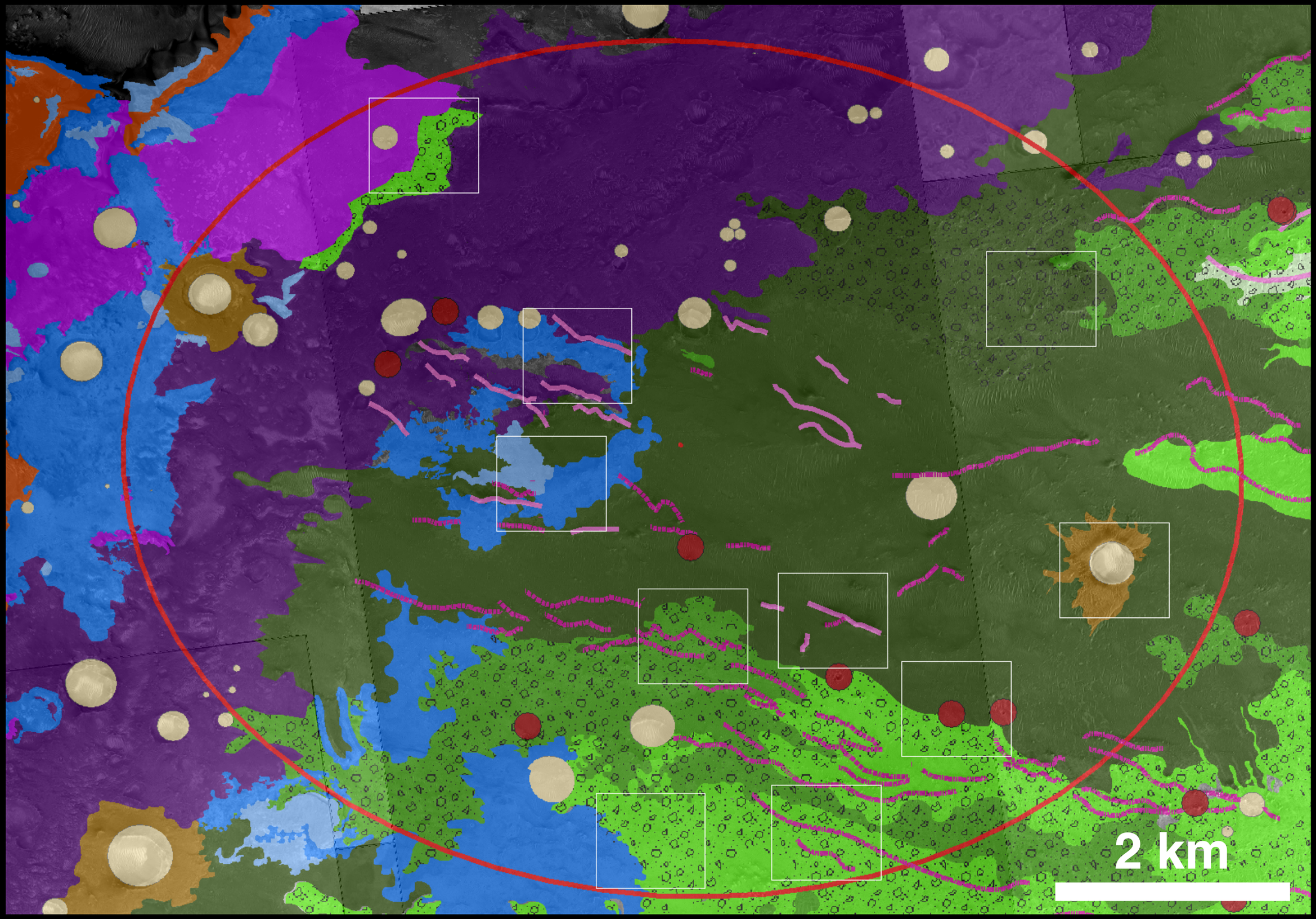
hydrated surface fractures in polygons in impact deposits

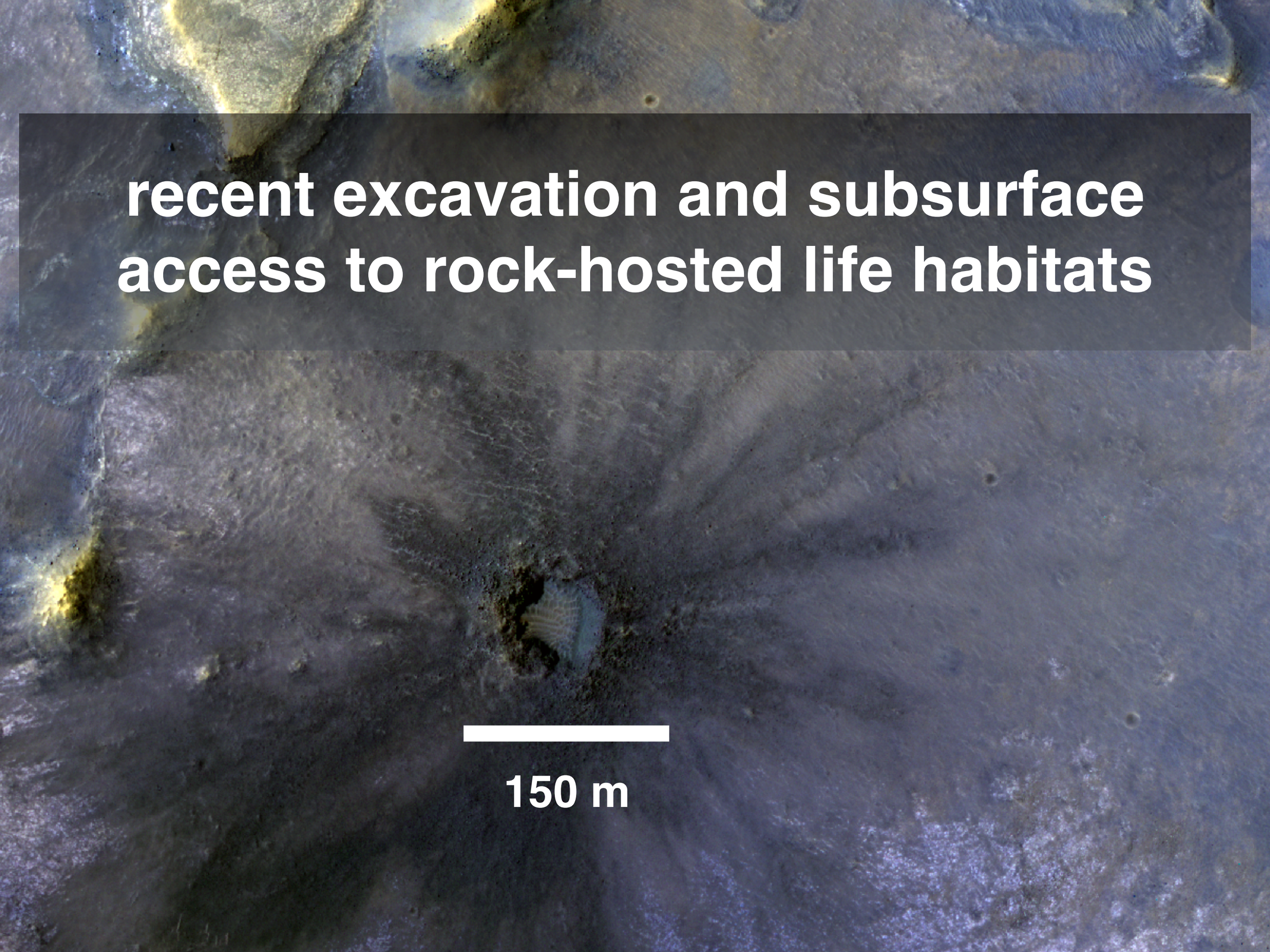
Toro Crater, Mars



Marzo et al 2010

Recent impacts: windows to the subsurface




recent excavation and subsurface access to rock-hosted life habitats
150 m

- impact breccia as a microbial habitat
- fracture systems and subsurface fluid conduits
- potential for volatile release due to impact induced hydrothermal activity
- rich geologic diversity; potential for (ancient: Noachian-Hesperian?) atmospheric component
- biosignature preservation in impact materials
- fundamental geologic process investigation: phyllosilicate associated with ejecta: excavation +/- hydrothermal alteration
- fresh impacts allow recent access to the ancient subsurface
- abundant geochemical, mineralogical, energetic interfaces
- ideal habitat for rock hosted life
- fundamental discoveries about deep biosphere - lessons for Earth