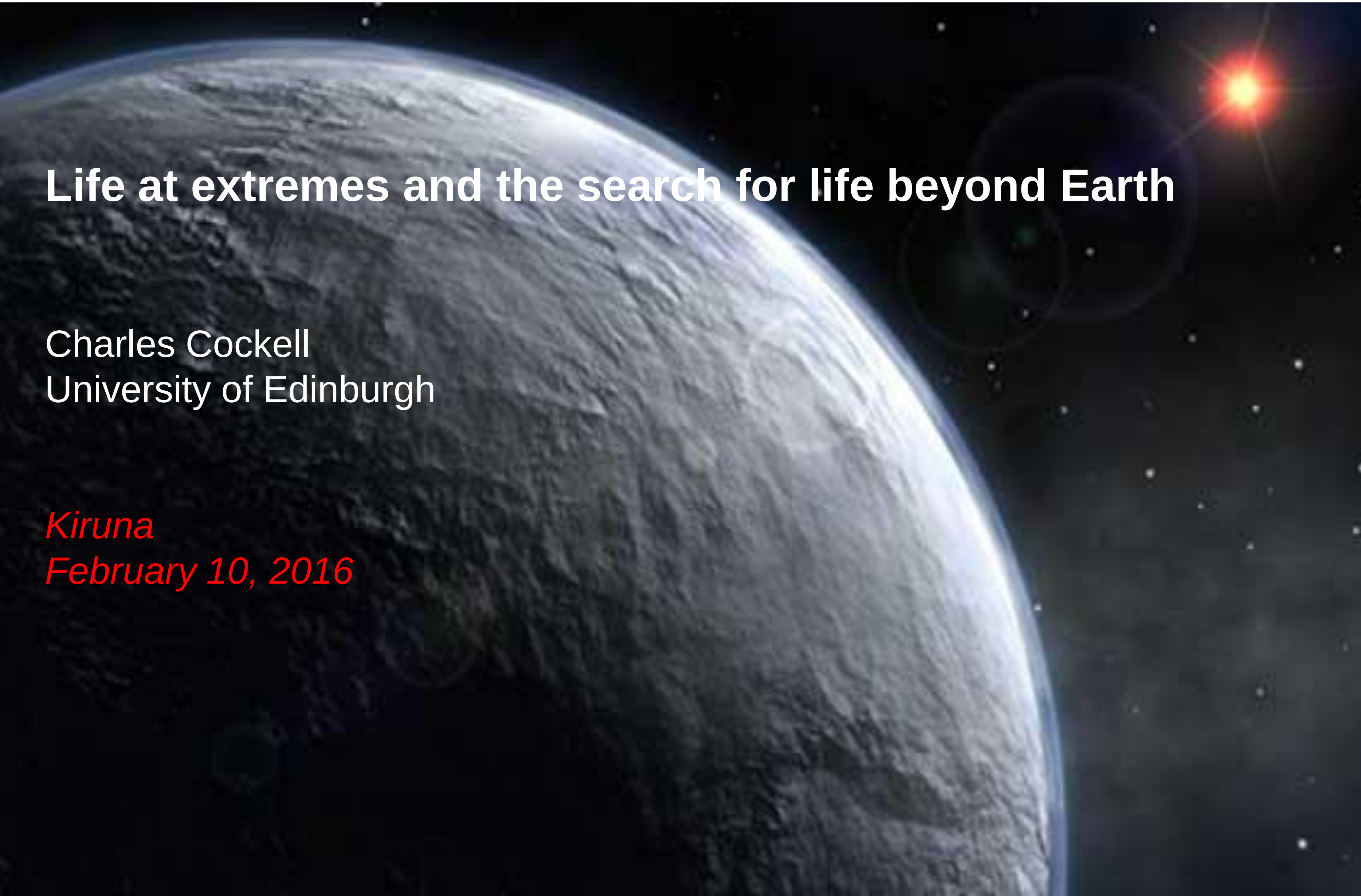


Life at extremes and the search for life beyond Earth

Charles Cockell
University of Edinburgh

Kiruna
February 10, 2016

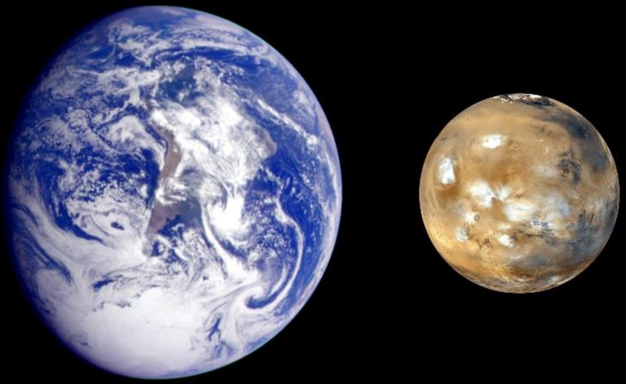
Astrobiology

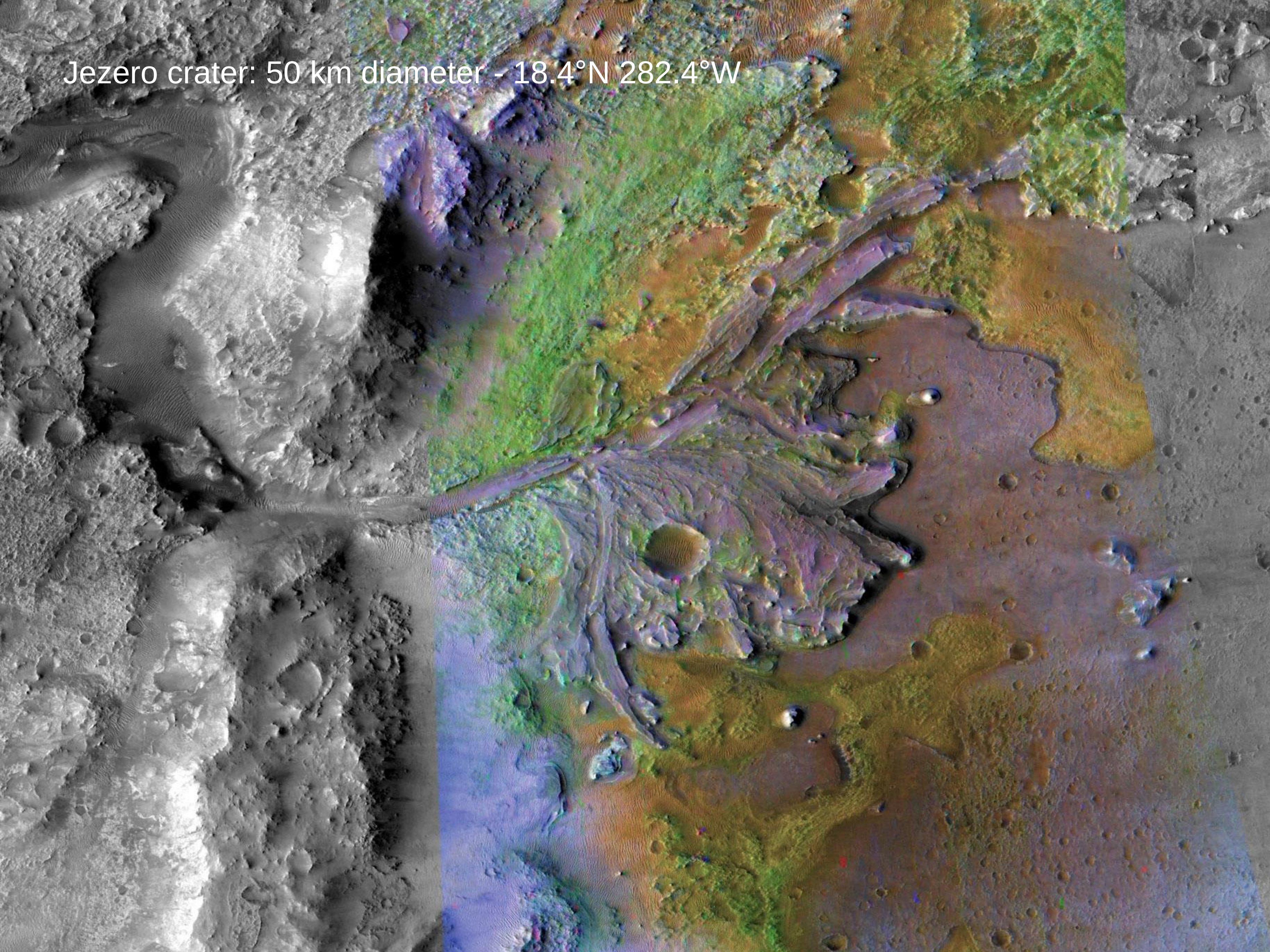
– the origin, evolution, distribution and future of life in the Universe

One of its most important questions:
‘Is there life elsewhere in the Universe?’

Astrobiology is now being driven by the discovery of diverse aqueous environments in the Universe

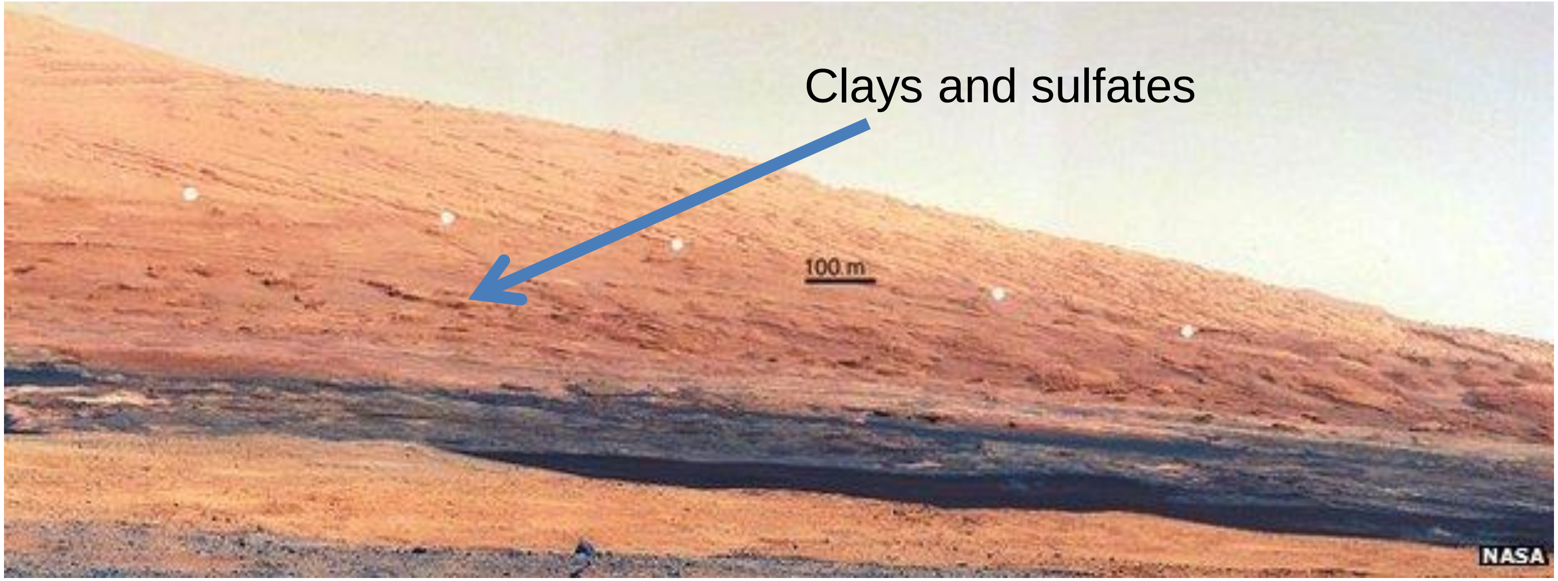
Mars



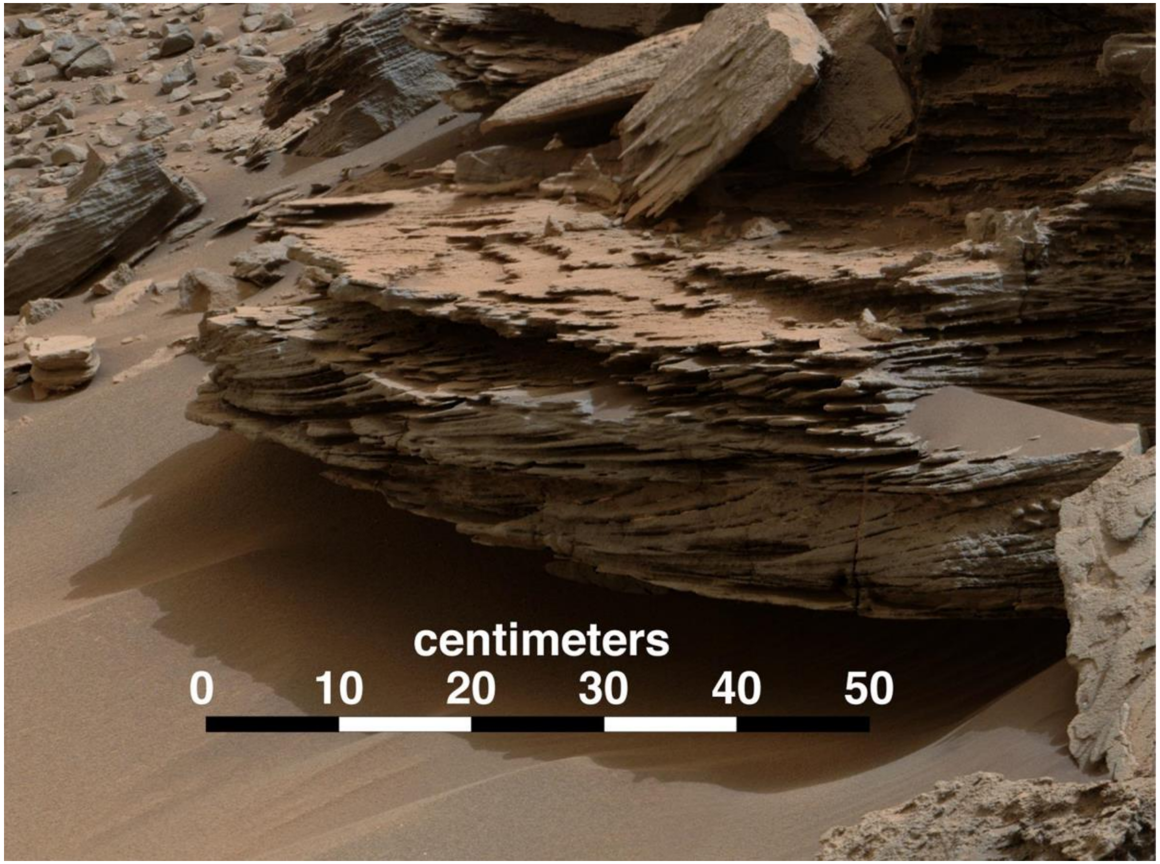

Jezero crater: 50 km diameter - 18.4°N 282.4°W


1 cm

Sediments from ancient lakes

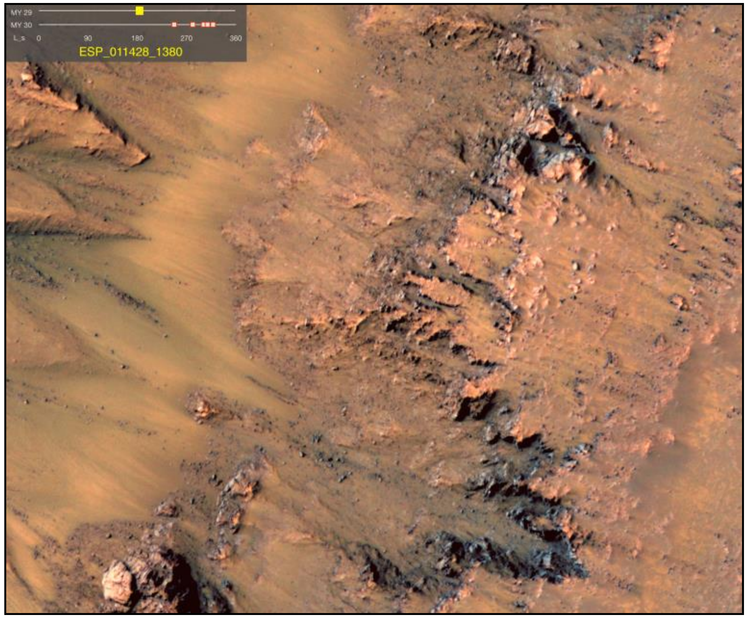


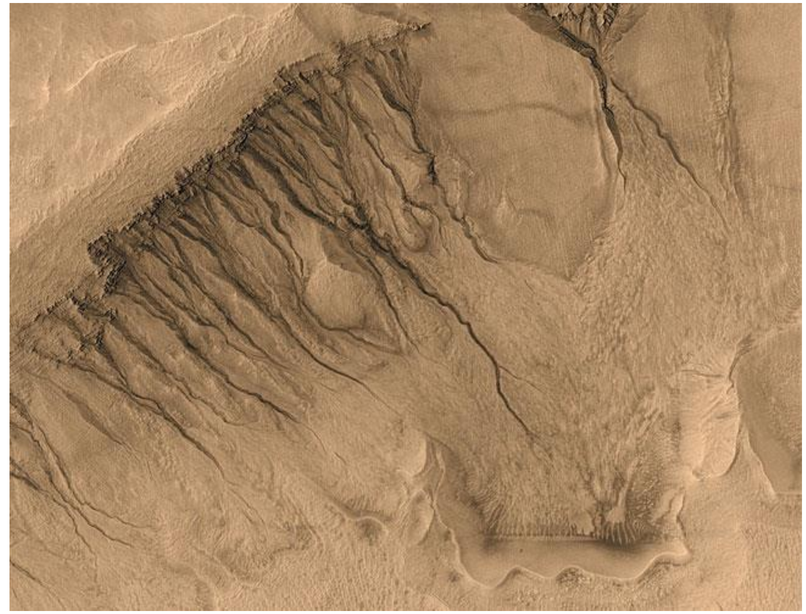
Sediments from ancient lakes

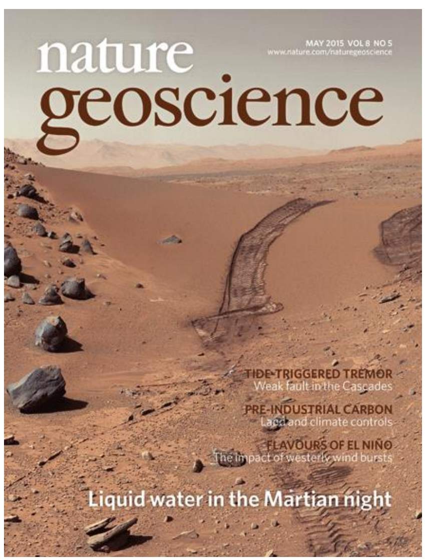


UK Centre for Astrobiology

Water on present day Mars?





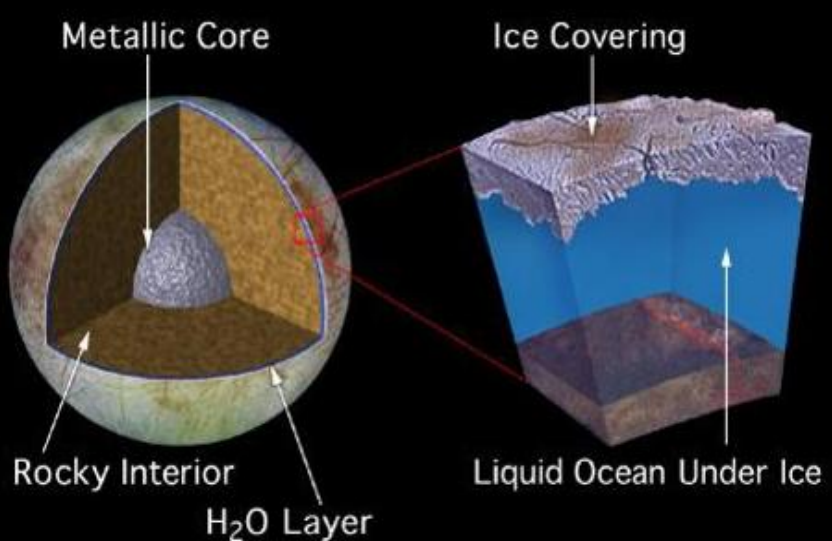


Martin-Torres FJ, Zorzano MP, Valentin-Serrano P, Harri AM, Genzer M, Kemppinen O, Rivera-Valentin EG, Jun I, Wray J, Madsen MB, Goetz W, McEwan AS, Hardgrove C, Renno N, Chevrier VF, Mischna M, Navarro-Gonzalez R, Martinez-Frias J, Conrad P, McConnochie T, Cockell C, Berger G, Vasavada AR, Sumner D, Vaniman D. 2015 Transient liquid water and water activity at Gale crater on Mars. *Nature Geoscience* DOI: 10.1038/NGEO2412.

In the Jovian system…

In the Saturnian system…

Europa



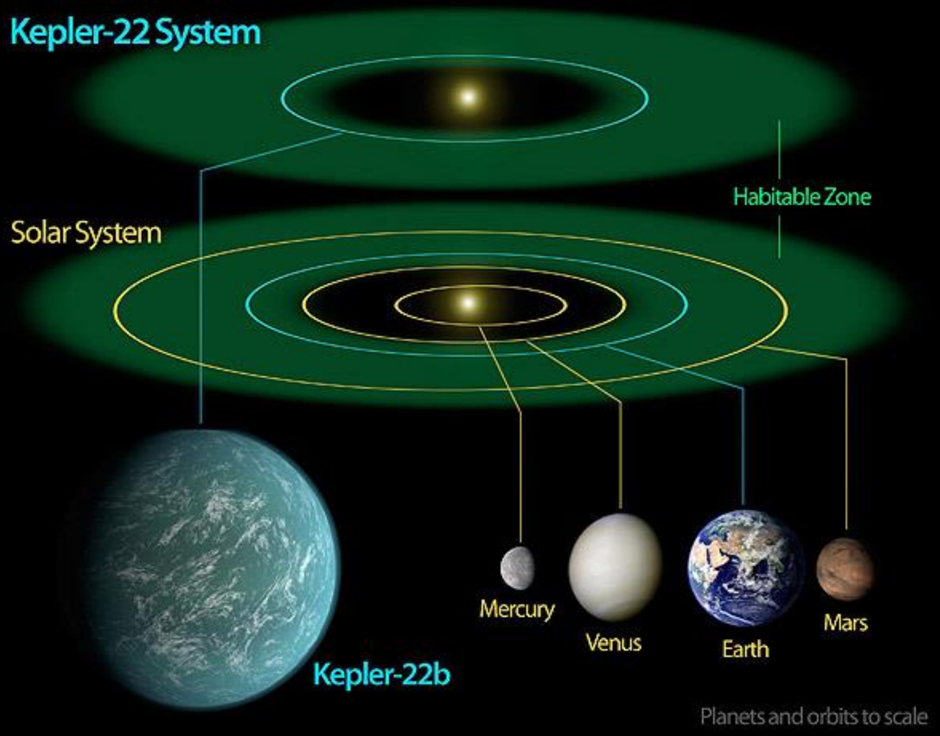
Enceladus

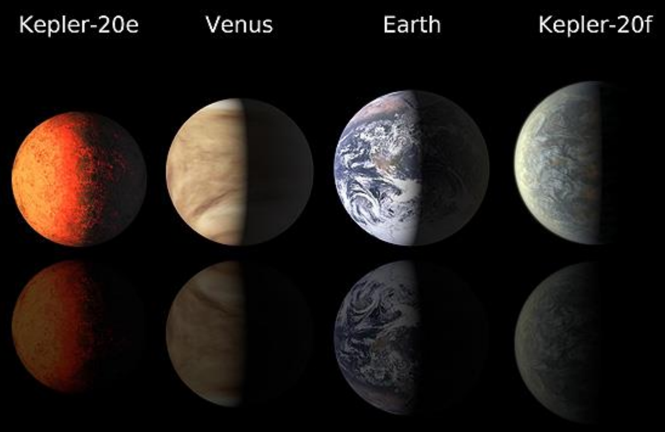
Table 1 | INMS determination of plume composition on 9 October 2008

Species	Volume mixing ratio
H_2O	0.90 ± 0.01
CO_2	0.053 ± 0.001
CO	[0.044]
H_2	[0.39]
H_2CO	$(3.1 \pm 1) \times 10^{-3}$
CH_3OH	$(1.5 \pm 0.6) \times 10^{-4}$
C_2H_4O	$<7.0 \times 10^{-4}$
C_2H_6O	$<3.0 \times 10^{-4}$
H_2S	$(2.1 \pm 1) \times 10^{-5}$
^{40}Ar	$(3.1 \pm 0.3) \times 10^{-4}$
NH_3	$(8.2 \pm 0.2) \times 10^{-3}$
N_2	<0.011
$HCN^{\dagger}$	$<7.4 \times 10^{-3}$
CH_4	$(9.1 \pm 0.5) \times 10^{-3}$
C_2H_2	$(3.3 \pm 2) \times 10^{-3}$
C_2H_4	<0.012
C_2H_6	$<1.7 \times 10^{-3}$
C_3H_4	$<1.1 \times 10^{-4}$
C_3H_6	$(1.4 \pm 0.3) \times 10^{-3}$
C_3H_8	$<1.4 \times 10^{-3}$
C_4H_2	$(3.7 \pm 0.8) \times 10^{-5}$
C_4H_4	$(1.5 \pm 0.6) \times 10^{-5}$
C_4H_6	$(5.7 \pm 3) \times 10^{-5}$
C_4H_8	$(2.3 \pm 0.3) \times 10^{-4}$
C_4H_{10}	$<7.2 \times 10^{-4}$
C_5H_6	$<2.7 \times 10^{-6}$
C_5H_{12}	$<6.2 \times 10^{-5}$
C_6H_6	$(8.1 \pm 1) \times 10^{-5}$

Looking for a second Earth

The search for Earth-like planets around distant stars





Current Potentially Habitable Exoplanets

Ranked in Order of Similarity to Earth

"8.8 billion habitable Earth-size planets exist in Milky Way alone"

Seth Borenstein, The Associated Press

Are any of these places habitable?

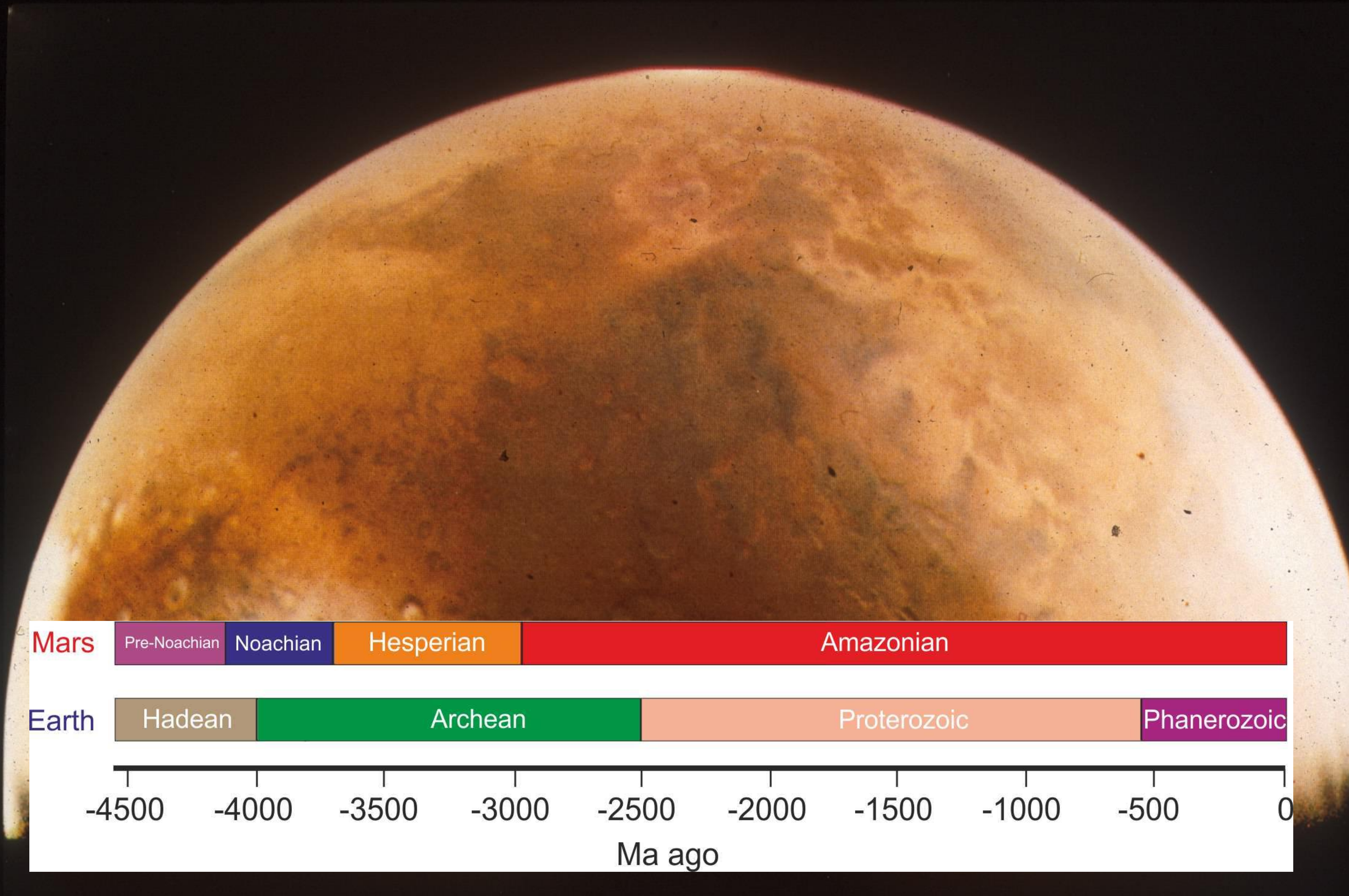
'The ability to support the activity of at least one known organism'.

In the short-term (Instantaneous habitability)

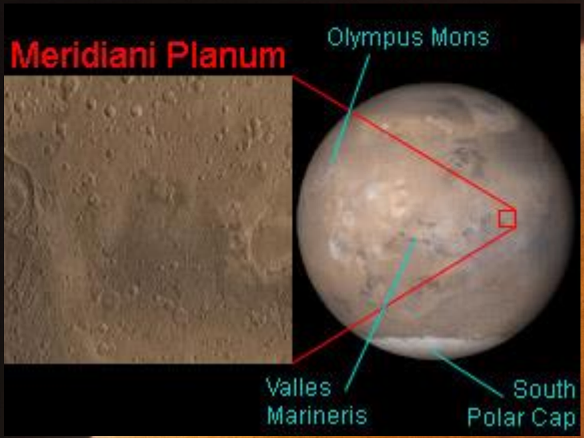
- CHNOPS
- Some other elements depending on organism
- Liquid (water)
- Energy
- Suitable physical and chemical conditions

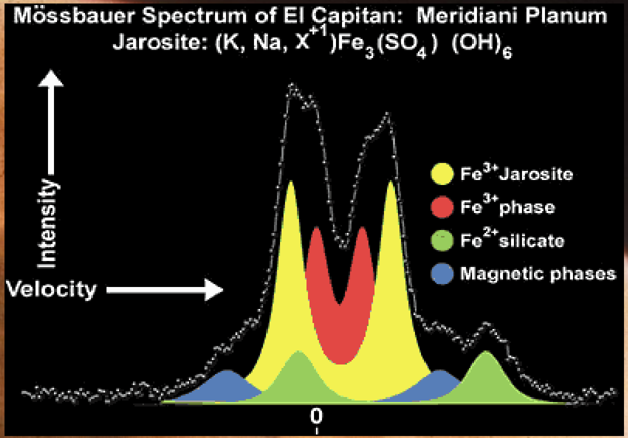
Cockell *et al.* (2016). Habitability: A Review. *Astrobiology*, 16, 1- 29

Are Martian brines habitable?



Mars went through a period of acidity in the Hesperian that produced lots of sulfate salts



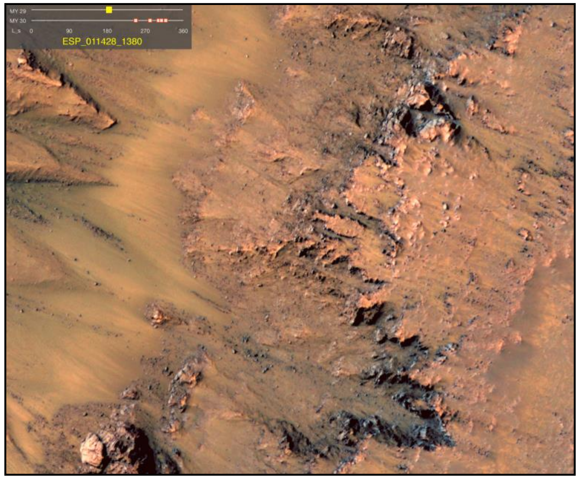


Martian aqueous environments

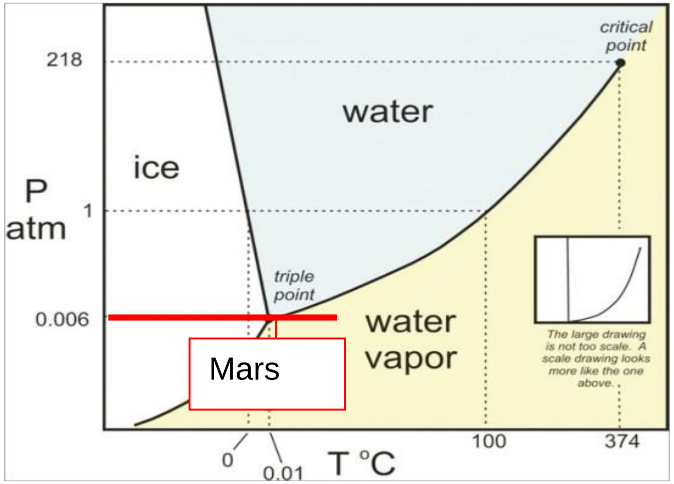
Widespread salt minerals indicate hypersaline waters over geologic timescales

Current and past surface conditions promote formation of concentrated brines.

Current brine activity?



HiRISE, University of Arizona



Were (are) Martian brine environments habitable?

On the Earth saline environments are physically stressful for biology, but they are often densely populated

BUT…

Terrestrial brines are very different than on Mars. They are largely dominated by monovalent ions: Na^+ and Cl^-

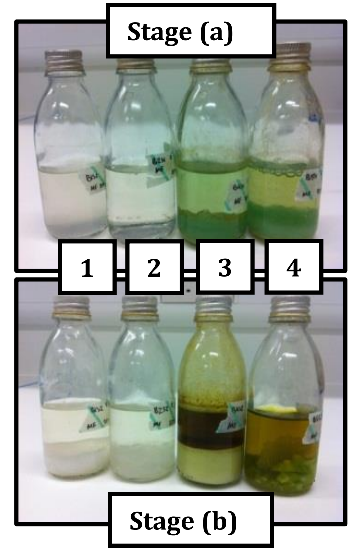
On Mars the acidic weathering of basaltic rock results in very different geochemistries

- Brines dominated by Mg and Fe sulphates

No known natural analogues exist on Earth

Experimental approach

Create artificial Martian brines in lab. Based on models and measurements from rovers and orbiters



Endeavoured to remove all stresses beyond those imposed by the brines:

- Rich nutrient source
- Moderate temperature
- Aerobic and anaerobic conditions

Two environmental inocula selected to capture both known salt-tolerant organisms and organisms exposed to different salts, sulfate lakes, Icelandic geothermal pools

Boulby Mine, North Yorkshire

Soil, Edinburgh

and left open to atmosphere for four months to maximise chances

- ‘Everything is everywhere…?’

Controls also made to isolate extremes:

- **C1**: low aw (0.800)
- **C2:** low pH (2.5)
- **C3:** Combined low pH (2.5) and reduced a_w (0.885)

- Triplicate enrichments incubated for 60 day periods.

Brine compositions

Table 2. Stage 1 Brine Compositions and Physical Properties[a]

	Brine 1(a)	Brine 2(a)	Brine 3	Brine 4(a)	Brine 5(a)	Brine 6(a)
HCO_3/SO_4	–	2.08	0.708	0.282	0.00	0.00
pH_f	6.86	5.59	4.19	4.02	1.37	−0.2
φ	0.9099	0.6485	1.0410	1.1863	1.2437	1.7626
IS (mol/kg)	0.1794	7.2803	12.5620	13.8330	13.6850	13.0740
a_{H2O}	0.9937	0.9543	0.8816	0.8525	0.8423	0.7350
ρ (g/cm^3)	1.0074	1.1934	1.2999	1.3056	1.3061	1.3247
η_{298} (mPa s)	0.8911	4.2160	15.2804	17.2060	16.6439	17.6663
η_{273} (mPa s)	1.7789	9.7807	40.3848	44.4396	42.5414	41.5753
P (Pa; 25°C)	3150.31	3024.9	2793.9	2701.2	2660.9	2178.5
σ (mN/m)	72.24	73.92	77.19	78.77	79.01	81.83
λ W/(m K)	0.6073	0.5790	0.5541	0.5470	0.5461	0.5110
κ (mS/cm)	13.71	69.71	42.1707	36.80	43.81	107.58
D_{H2O} (m^2/s)	2.30E-09	1.53E-10	5.51E-11	2.84E-11	3.65E-11	1.88E-10
D_{Mg} (m^2/s)	6.91E-10	3.95E-11	2.64E-11	1.39E-11	1.76E-11	7.84E-11
D_{SO4} (m^2/s)	–	6.09E-11	1.97E-11	1.00E-11	1.29E-11	6.82E-11
D_{Na} (m^2/s)	1.29E-09	9.91E-11	4.02E-11	2.09E-11	2.67E-11	1.27E-10
D_H (m^2/s)	8.56E-09	6.13E-10	2.79E-10	1.46E-10	1.86E-10	8.38E-10
C_p (J/(kg K))	4133.16	3251.31	2918.3554	2777.72	2851.97	3410.23
Na	0.1250	0.1288	0.12883	0.1444	0.1649	0.1743
K	0.0500	0.0515	0.0515	0.0578	0.0659	0.0697
Ca	0.0004	0.0071	0.00207	0.0014	0.0015	0.0028
Mg	0.0010	1.7800	2.5611	2.3485	2.3095	2.1936
Fe(II)	0.0000	0.0018	0.55851	1.0980	1.0984	0.9535
Cl	0.0250	0.2576	0.38649	0.5200	0.6594	0.8368
SO_4	0.0000	1.7331	3.0165	3.2870	3.1630	2.3340
HCO_3	0.1526	0.0344	0.0044	0.0042	0.0000	0.0000
HSO_4	0.0000	0.0000	0.0000	0.0003	0.1277	2.0851
CO_3	1.34E-04	0.0000	0.0000	0.0000	0.0000	0.0000

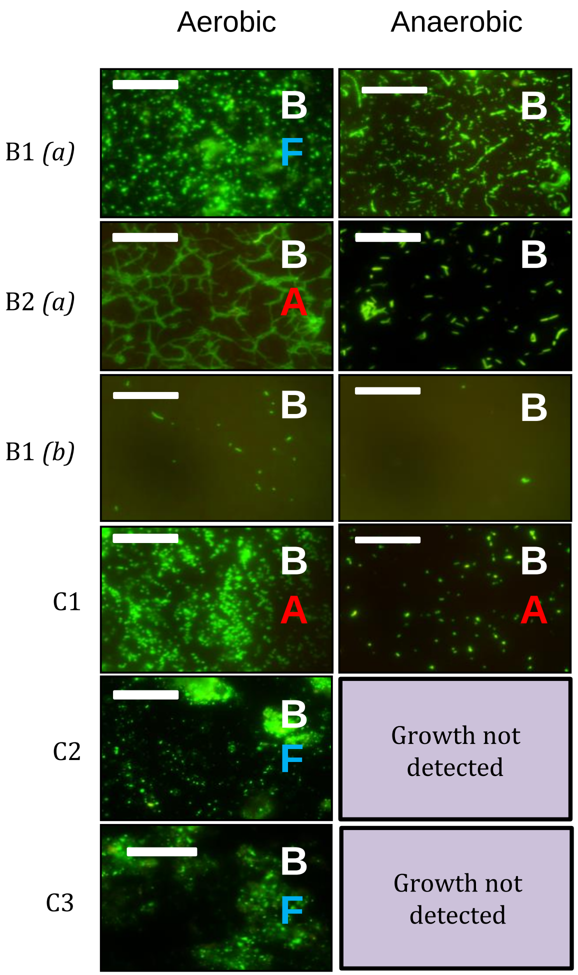
[a]All values are at 25°C unless otherwise noted. Compositions are in mol/kg.

Table 4. Saline Mineralogy From Evaporation and Freezing Simulations[a]

	Brine 1(a)	Brine 1(b)	Brine 2(a)	Brine 2(b)	Brine 3	Brine 4(a)	Brine 4(b)	Brine 5(a)	Brine 5(b)	Brine 6(a)	Brine 6(b)
Evaporation Simulation											
Siderite	34.97	33.82	52.98	36.17	35.13	21.40	0.52	–	–	–	–
Calcite	16.21	15.67	–	–	–	–	–	–	–	–	–
Magnesite	48.82	47.21	22.62	15.59	–	–	–	–	–	–	–
Gypsum	–	–	24.40	16.66	16.97	39.15	95.39	32.93	17.48	29.15	17.67
Melanterite	–	–	–	–	–	17.98	1.37	37.72	34.04	38.69	37.06
Epsomite	–	–	–	31.30	47.90	21.47	2.72	29.34	48.48	32.16	31.24
Bloedite	–	–	–	0.24	–	–	–	–	–	–	–
Kieserite	–	–	–	–	–	–	–	–	–	–	14.01
Halite	–	–	–	–	–	–	0.01	–	–	–	0.01
Picromerite	–	–	–	0.04	–	–	–	–	–	–	–
KCl	–	0.46	–	–	–	–	–	–	–	–	–
$NaHCO_3$	–	2.37	–	–	–	–	–	–	–	–	–
$KHCO_3$	–	0.47	–	–	–	–	–	–	–	–	–
Freezing Simulation											
Siderite	35.00	–	47.00	33.33	33.33	–	–	–	–	–	–
Calcite	16.21	0.33	–	–	–	–	–	–	–	–	–
Magnesite	48.79	2.26	19.73	–	–	–	–	–	–	–	–
Gypsum	–	–	21.46	21.87	21.87	21.14	0.42	21.06	1.05	17.30	–
Melanterite	–	–	–	4.10	4.10	37.96	27.59	37.88	–	36.45	20.22
$MgSO_4$ $12H_2O$	–	–	11.81	40.70	40.70	40.90	61.34	41.05	67.90	46.26	56.38
$NaHCO_3$	–	82.50	–	–	–	–	–	–	–	–	–
$KHCO_3$	–	14.92	–	–	–	–	–	–	–	–	–
KCl	–	–	–	–	–	–	6.06	–	4.51	–	–
NaCl $2H_2O$	–	–	–	–	–	–	–	–	6.80	–	–
Mirabilite	–	–	–	–	–	–	4.60	–	2.37	–	1.66
$MgCl_2$ $12H_2O$	–	–	–	–	–	–	–	–	17.37	–	–
$KHSO_4$	–	–	–	–	–	–	–	–	–	–	15.03
$Na_3H(SO_4)^2$	–	–	–	–	–	–	–	–	–	–	6.71

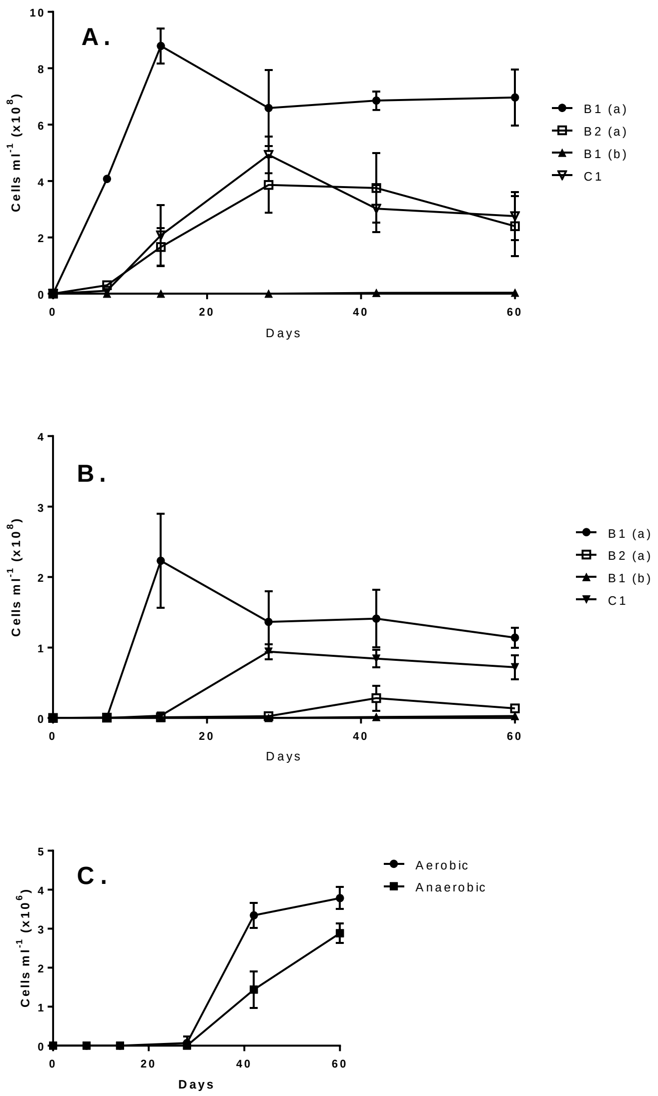
[a]Note that simulations are not carried to absolute completion but in a maximum of two stages only.

Microbial communities in simulated Martian brines



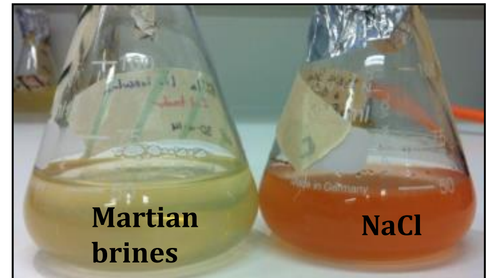
*Scale bars = 20 µm

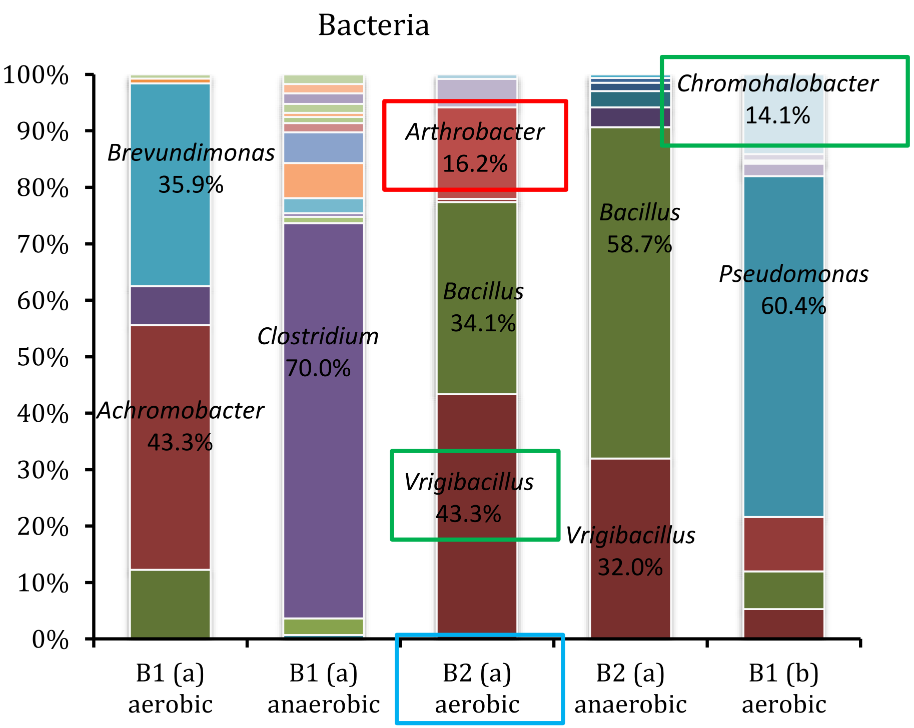
- Communities interrogated with domain-specific PCR

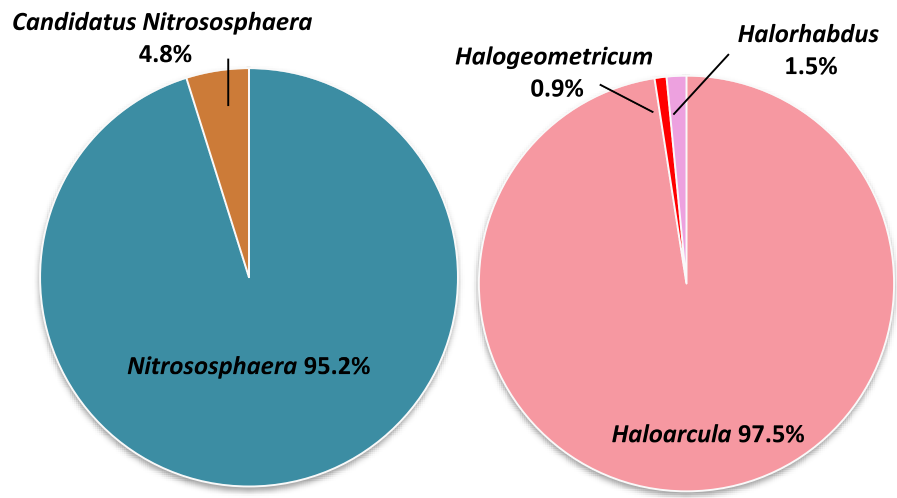


Microbial communities in simulated Martian brines

- Taxonomically distinct, unique communities of bacteria
- Organisms from NaCl brine (Boulby) conspicuously lacking.
- Included groups with known salt-tolerance as well as groups not commonly found in brine environments.



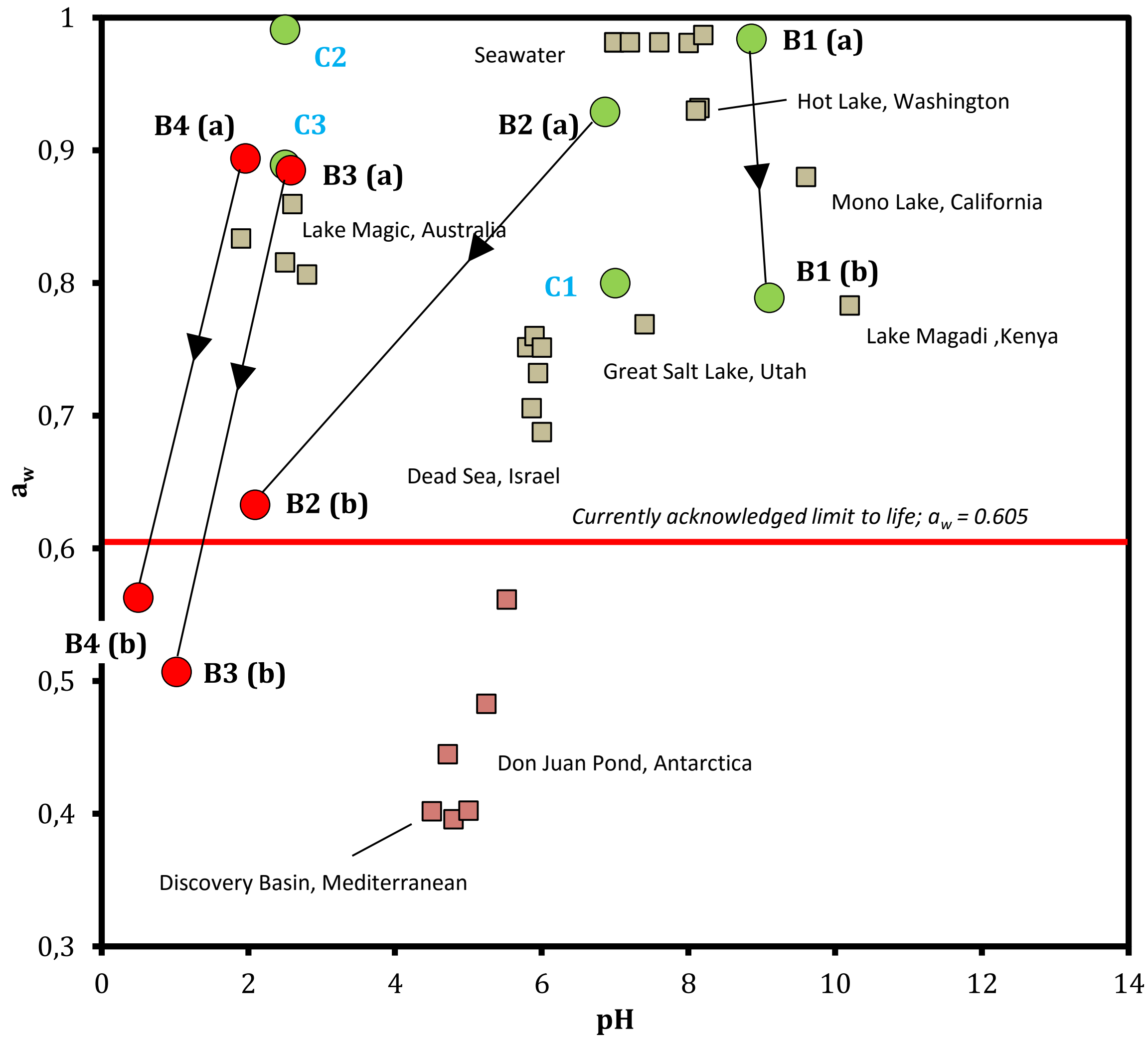




- Halophilic archaea dominate chloride brins
- Haloarchaea absent from Martian brines

Habitability of Mars-relevant brines: water activity does not predict habitability as on Earth

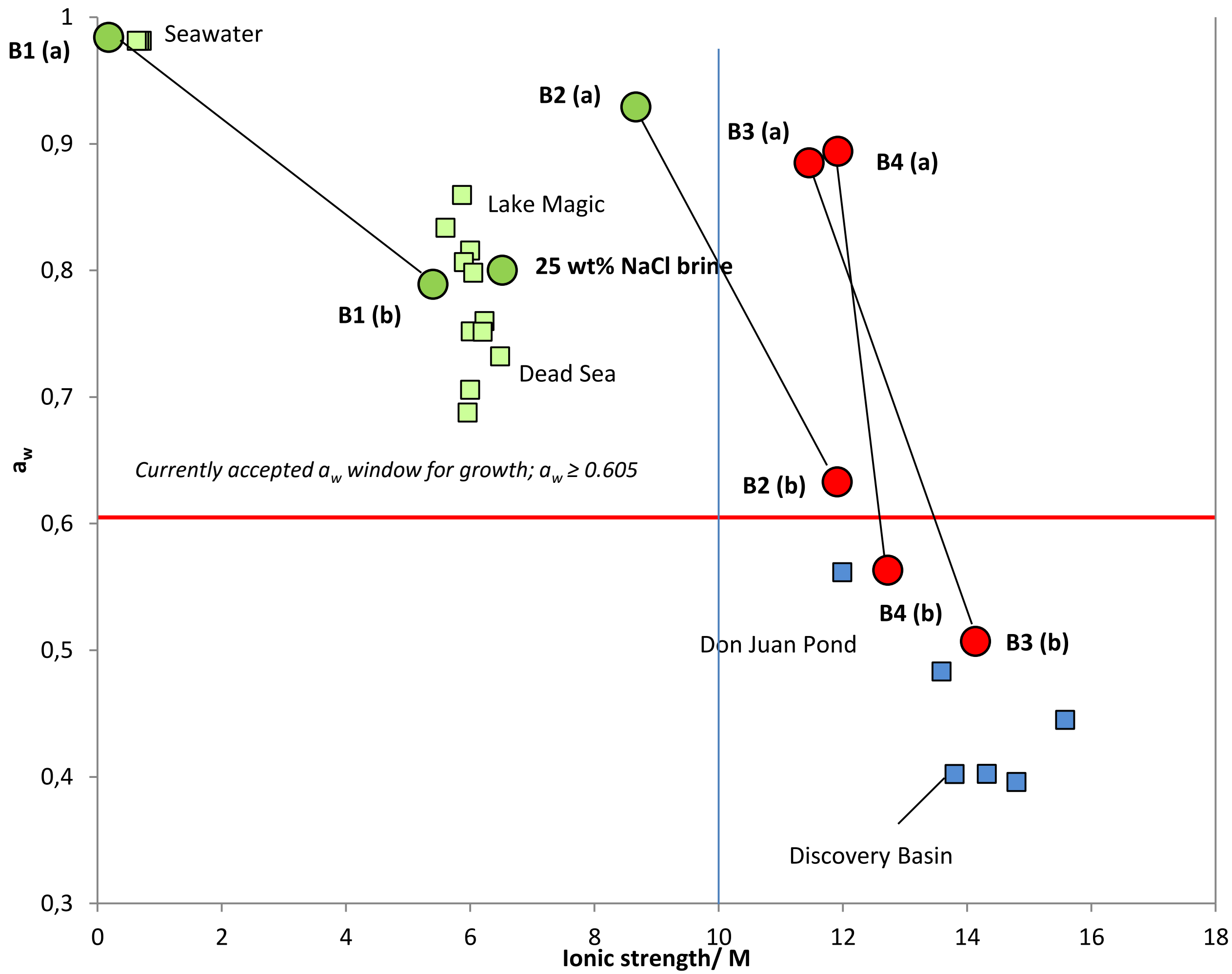
- Water activity defines the limits to habitability in terrestrial NaCl brines
- Only 3 Mars-relevant brines supported the growth of any organism
- Thermodynamically available water is not enough: Water activity (a_w) **does not predict Martian brine habitability**



Martian brine habitability

Ionic strength vs. a_w

- Ionic strength: a more suitable predictor of habitability than a_w?
- Ionic strength defines an important stressor for Martian brine habitability
- **WHY? Because Martian brines have multivalent ions (Mg^{2+}, $Fe^{2+/3+}$, SO_4^{2-}) that lead to high ionic strength**

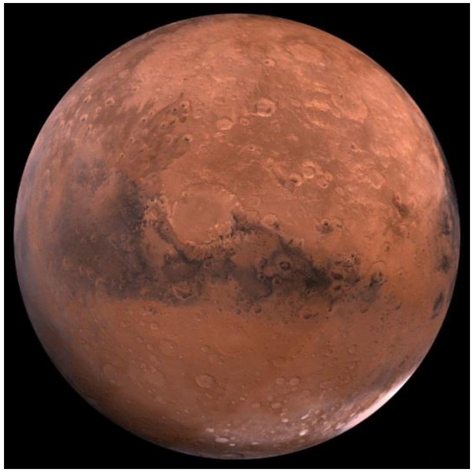


Geochemical history of Mars/Earth

What limits life?

Ionic strength

Mg^{2+}, SO_4^{2-}



Multivalent ions

Sulfate dominated brines

What limits life?

Water activity: a_w

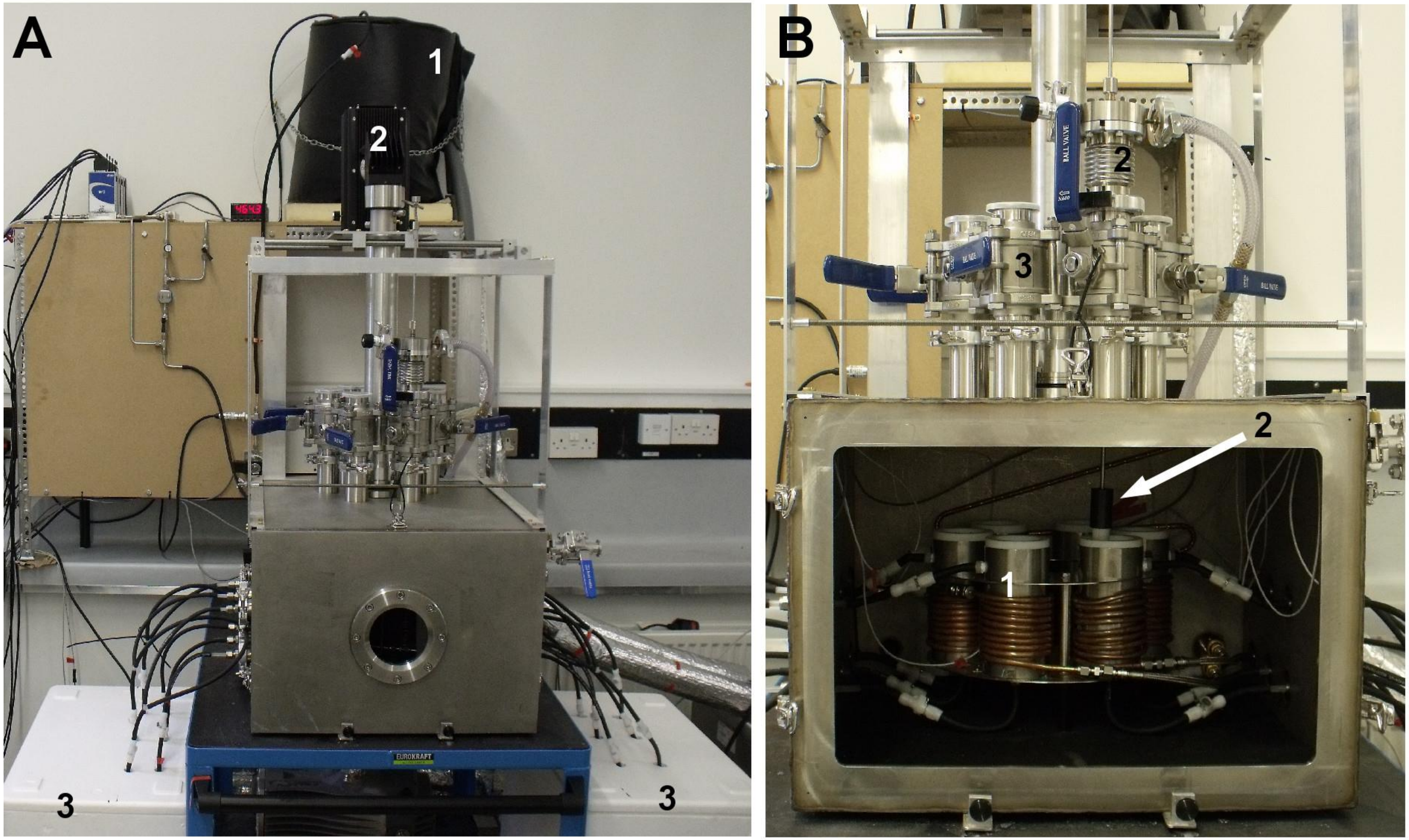
Na^+, Cl^-

Monovalent ions

Chloride dominated brines

Extraterrestrial aqueous simulation facility

- A new instrument for studying the habitability of alien geochemistries



Martin, D., Cockell, C.S. 2015. PELS (Planetary Environment Liquid Simulator), a new type of planetary simulation facility with liquid flow through to study extraterrestrial aqueous environments. *Astrobiology* 15, 111-118.

THE HABIT INSTRUMENT

(HabitAbility: Brines, Irradiation, and Temperature)

ExoMars Surface Science Package 2018

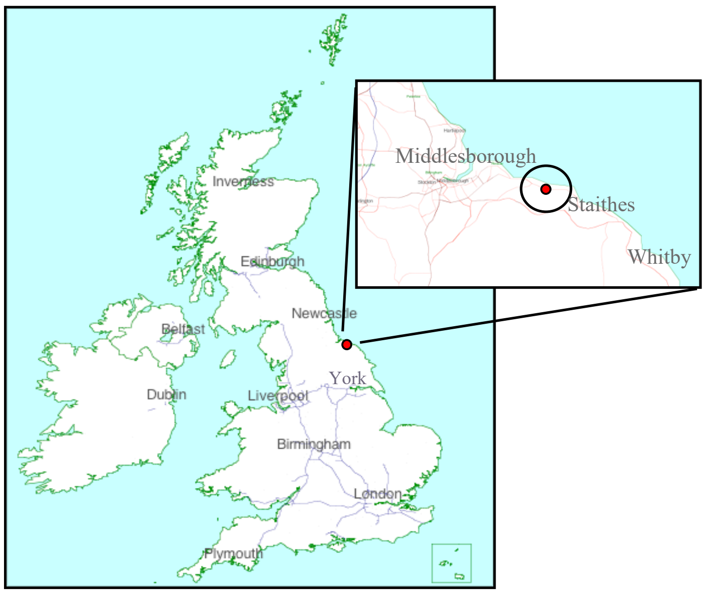
European Space Agency

Life Deep Underground

Boulby Mine - A working potash and rock-salt mine on the North East of England.

Operated by Cleveland Potash Ltd.

Major local employer - ~1000 direct and 4000 indirect employment.



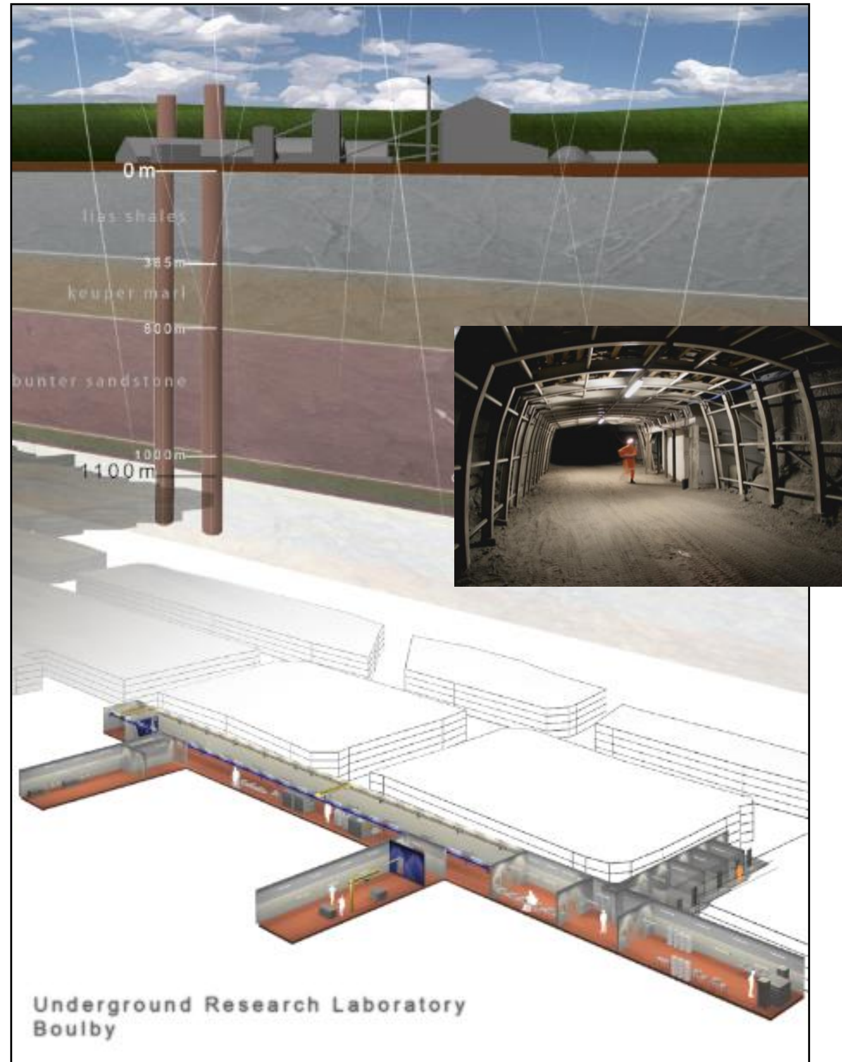
Deepest mine in Britain – 1100m deep

Potash

`View from Staithes

Boulby Science facilities

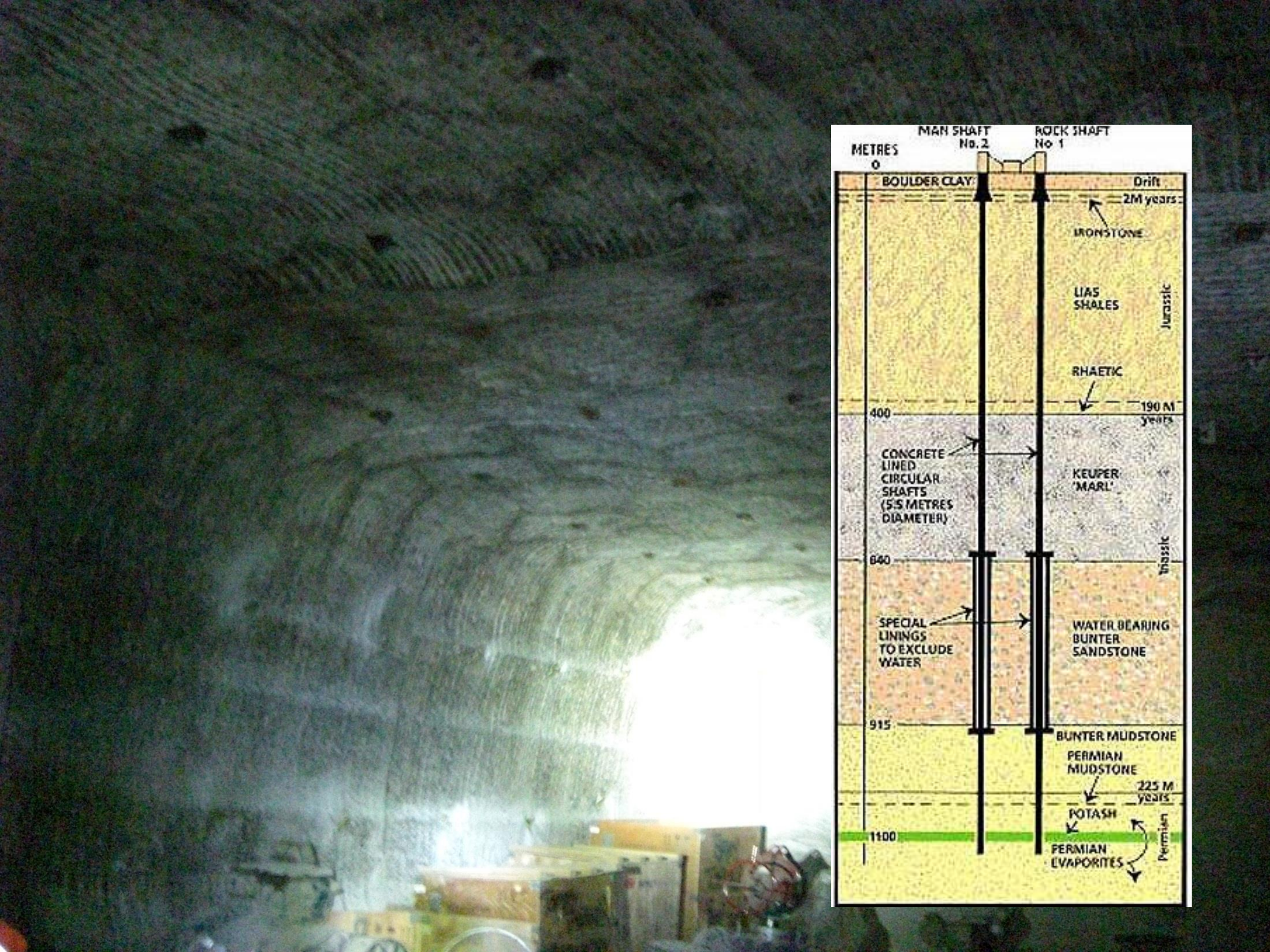
- ‘Palmer Lab’: a 100+m, fully equipped underground lab. Power, internet and telephone communications, lifting, air conditioning / filtration, clean room.
- ‘John Barton’ surface facility: Workshop, facility monitoring, office and administration, PPE, storage, chemistry lab, changing rooms.




BISAL
Boulby International Subsurface Astrobiology Lab

The Zechstein Sea

- an epicontinental sea that existed in the Guadalupian and Lopingian epochs of the Permian period (~270-250 Mya ago)



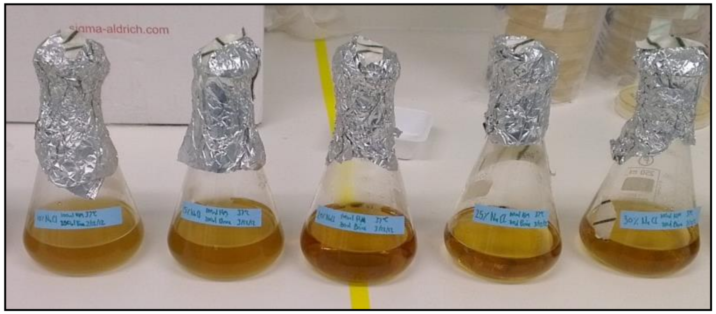
MAN SHAFT
No. 2
ROCK SHAFT
No 1
METRES
0
BOULDER CLAY
Drift
2M years
IRONSTONE
LIAS
SHALES
Jurassic
RHAETIC
190 M
years
400
CONCRETE
LINED
CIRCULAR
SHAFTS
(5.5 METRES
DIAMETER)
KEUPER
'MARL'
Triassic
640
SPECIAL
LININGS
TO EXCLUDE
WATER
WATER BEARING
BUNTER
SANDSTONE
915
BUNTER MUDSTONE
PERMIAN
MUDSTONE
225 M
years
POTASH
1100
PERMIAN
EVAPORITES
Permian

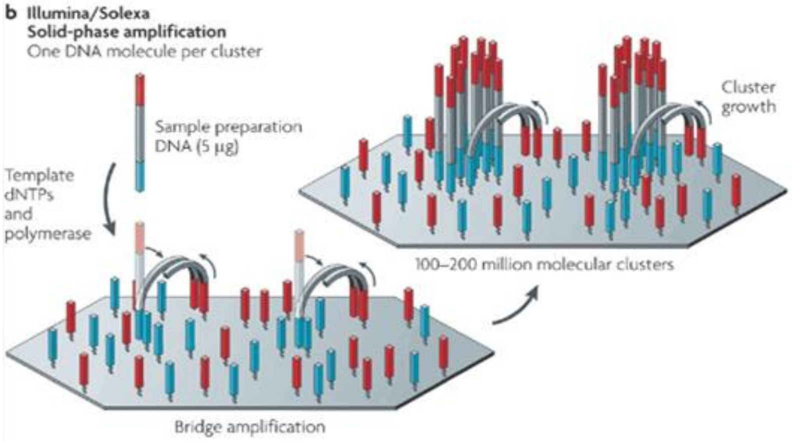
Study of Deep Brine Seeps

- What is the nature of the geochemical environment?
- What organisms are present?
- What are those organisms capable of doing?

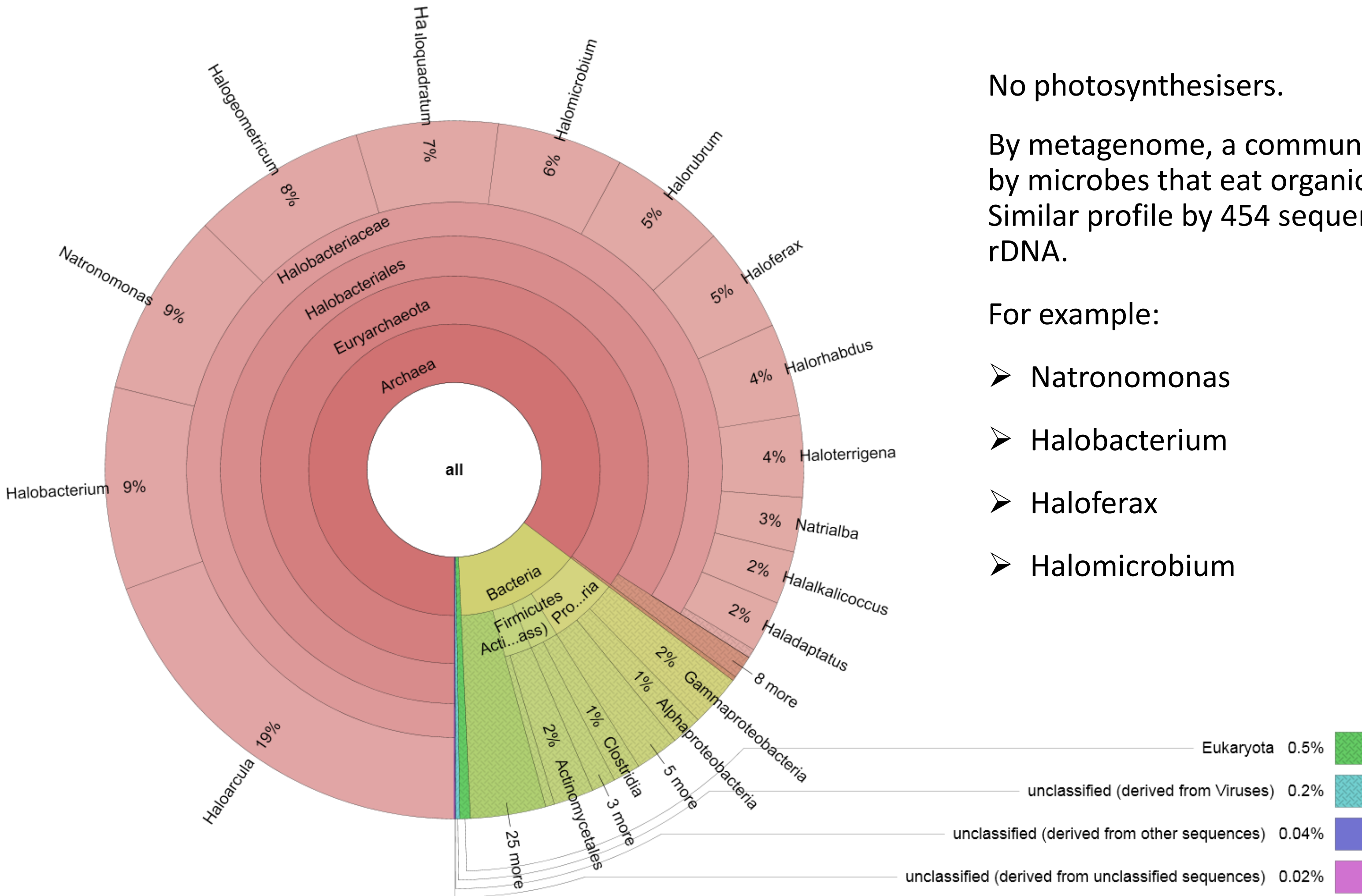
Methods

- Geochemical analysis
- 16S rRNA Amplicon sequencing
- Metagenomics
- Culturing
  - Aerobic
  - Anaerobic





Life in deep, dark salts



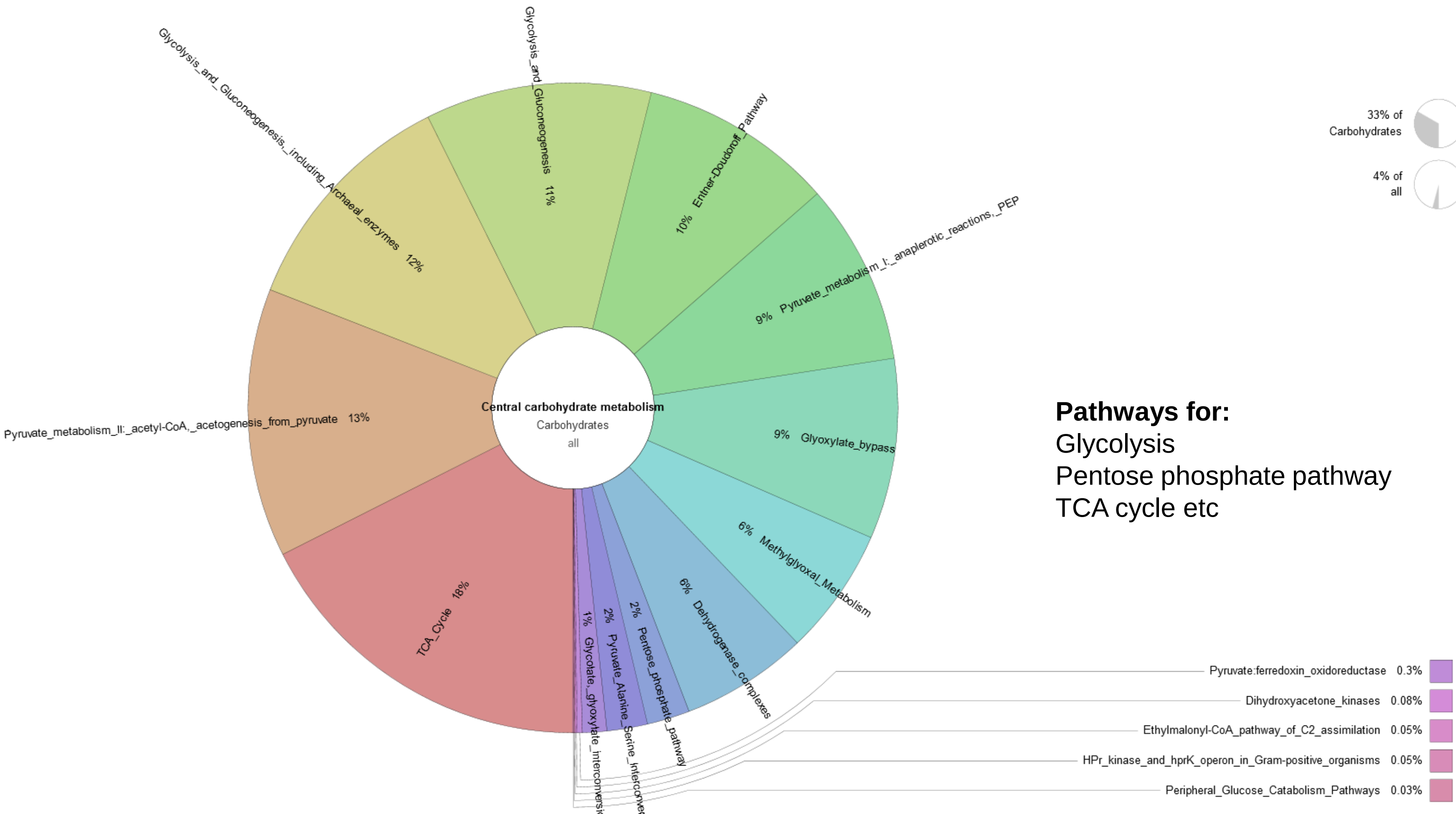
No photosynthesisers.

By metagenome, a community dominated by microbes that eat organic material. Similar profile by 454 sequencing of 16S rDNA.

For example:

- Natronomonas
- Halobacterium
- Haloferax
- Halomicrobium

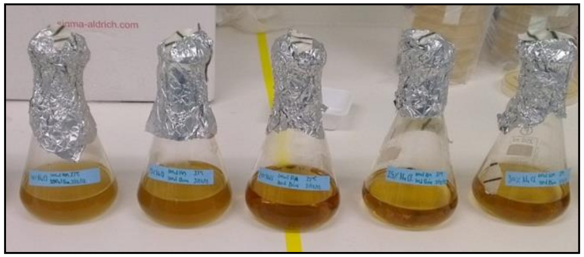
Metagenomics allows us to study the pathways of carbon use



Pathways for:
Glycolysis
Pentose phosphate pathway
TCA cycle etc

Culture microbes

Attempting to grow organisms on a variety of carbon sources.



We find that they grow on:

- Simple organic compounds (e.g. acetate)
- Complex organic compounds (xylan etc)
- Other hydrocarbons from the mine

The deep subsurface of the salts is inhabited by a diverse microbial community, but it is dependent on organics supplied from outside the salts. This includes organics from deeper Carboniferous sediments and organics from the aquifer above. The organisms take part in carbon cycling in the deep subsurface.

Much of these organics originally came from photosynthesis showing that deep subsurface microbial communities ultimately depend on the surface photosynthetic biosphere with implications for the potential productivity of extraterrestrial subsurface environments.

Expedition 364: Drilling the end-Cretaceous Impact crater

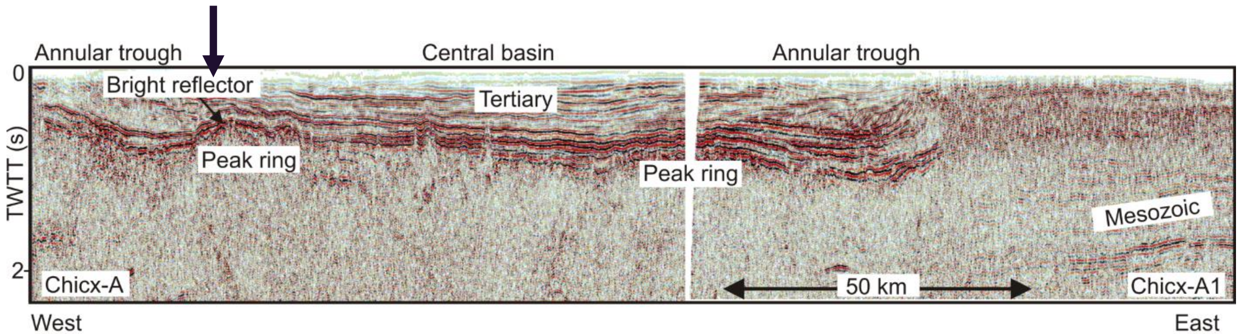
Co-chiefs Sean Gulick and Joanna Morgan

Expedition 364

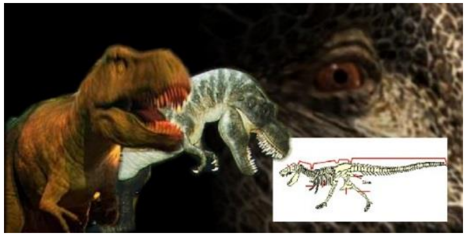
Joint IODP-ICDP drilling of peak ring of Chicxulub impact crater (Chicx-03A) April 2016

Objectives: understanding impact crater formation, post impact microbiology and recovery of ecosystems following impact at the end-Cretaceous

Chicx-03A drill hole into peak ring



Reflection data across the Chicxulub impact basin



After

Now?

Peak ring is likely formed of fractured, porous rock, submerged in water, adjacent to thick hot melt sheet and likely contains hydrothermal minerals yielding important insights into the post-impact environment, geology and microbiology.

The mission of the UK Centre for Astrobiology is to advance our understanding of molecules and life in extreme environments on the Earth and beyond. It does this by a combination of theoretical, laboratory, field and mission approaches. We apply this knowledge to improving the quality of life on Earth and developing space exploration as two mutually enhancing objectives.

www.astrobiology.ac.uk

Science

- Astrobiology Consortium grant
- First large scale astrobiology grant from research council (£1 million)
- 2015-2018
- Investigating life at micron-scales and experiments for the international space station.

- NASA grant under Planetary Science and Technology Analogue Research
- Biology leads
- Project seeks to investigate life and biosignatures in volcanic terrains
- Test technology for robotic and human exploration of Mars

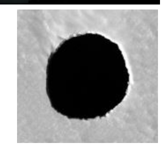
- EU Space grant
- Scientific Coordination
- 2.5 million Euro
- To investigate anaerobic organisms in extreme Mars analogue environments.
- Investigate response of organisms to stresses associated with the Martian environment

- Projects with UK Space Agency to study habitability of Martian brines and biofilms in space

- Involvement in CLUPI, HABIT ExoMars teams

UK Centre for Astrobiology

Technology transfer

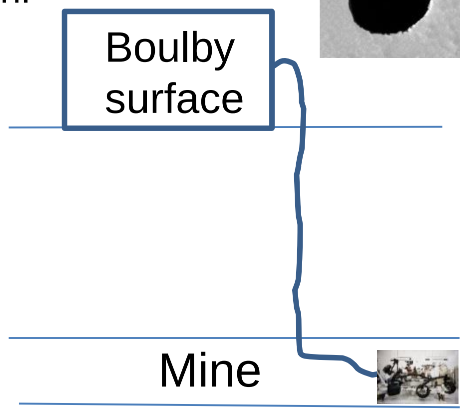


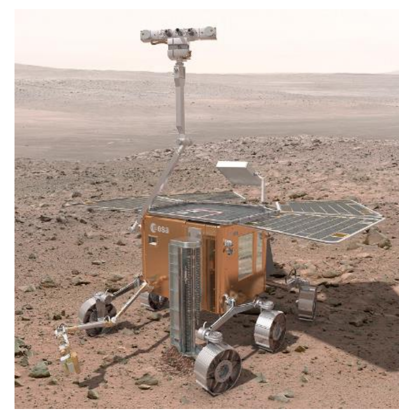
THE CROWN ESTATE

MINAR Mine Analogue Research

Integrated test of planetary instrumentation:

- Panoramic Camera (PanCam)
- Raman instrument
- CLUPI (Close-Up Imager)
- SPLIT
- XRF
- XRD
- ATP analysis
- Ultrasonic drilling

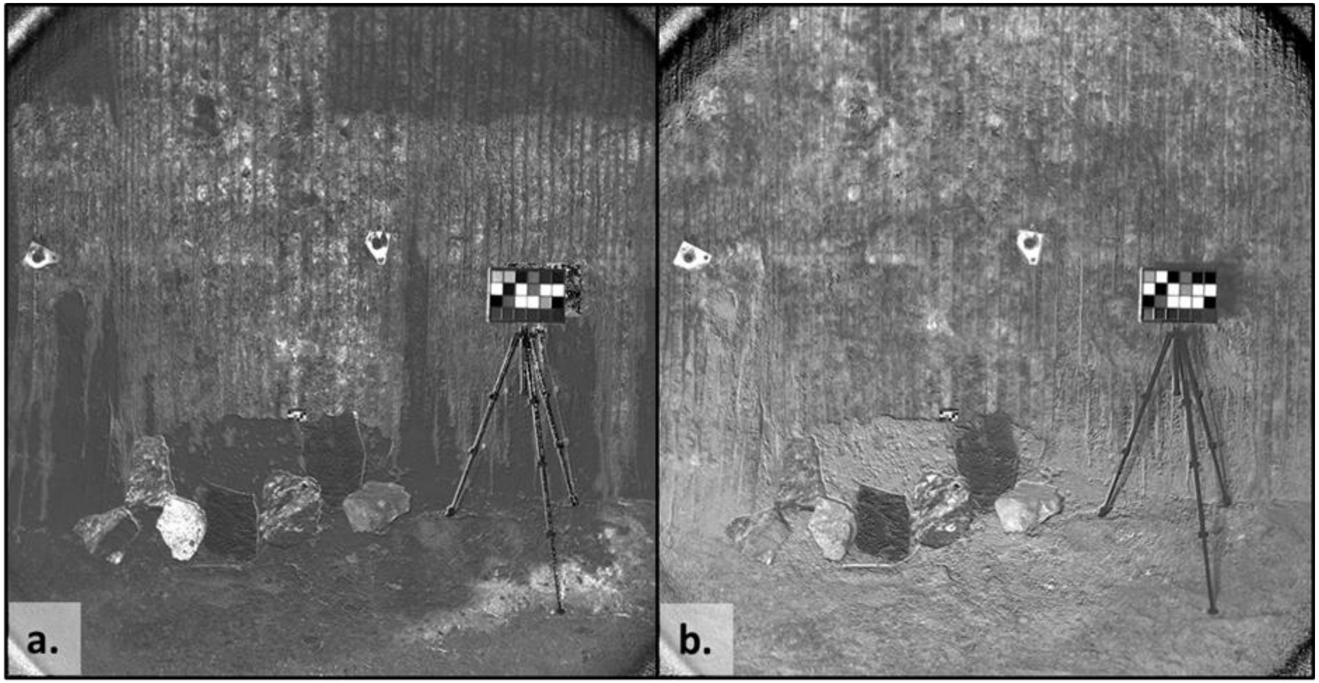




- Three campaigns already completed
- Tests for the subsurface exploration of other planets
- Technology identified for improving access to ores

Technology transfer

Seeing through salt… to better mine ore
- Using planetary science instruments



PanCam imager for ExoMars.
Spectral Parameter maps generated using the 438nm and 671nm filters - a. Red / Blue Ratio, b. Blue / Red slope.

UK Centre for Astrobiology

Teaching

Massive Open On-line Course

"Astrobiology and the Search for Extraterrestrial Life"
- A Massive Open On-line Learning Course (MOOC)

www.coursera.org

- One of 6 Edinburgh courses
- Five weeks of 32 lectures on-line
- Available on demand
- Over 80,000 people have now used the course
- Over 15,000 have completed

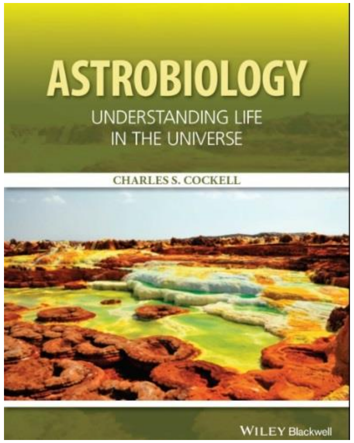
Astrobiology Summer Academy

- **Third summer of Astrobiology Summer Academy in 2015**
- Lesson plans written which have been used by greater than 1000 teachers across the UK.
- Uses lesson plans in astrobiology to teach science including biology, chemistry, physics.
- These are openly available on TES Resources.

Astrobiology textbook

Textbook in November 2015

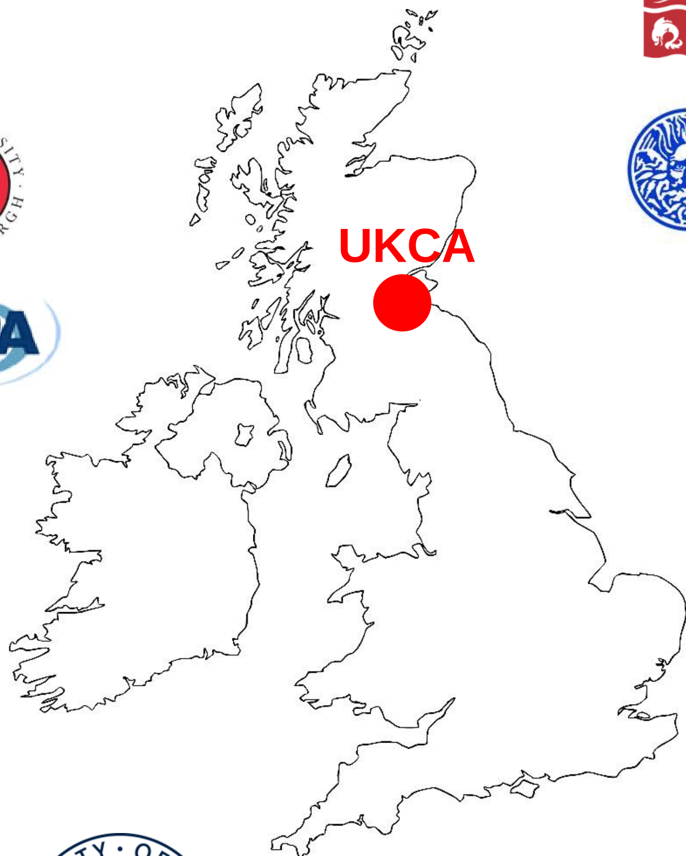
- Published by Wiley-Blackwell
- Undergraduate level
- Powerpoint slides for 21 lectures on-line to allow anyone to set up an astrobiology course



Undergraduate course

- **Undergraduate course in astrobiology in third year (attracts ~ 130 students)**
- **Has been running for three years**
- **Potential for advanced courses in later years**
- **Joint degree course**

The UKCA has links to astrobiologists at other universities



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The University of Edinburgh
SUPA
Queen's University Belfast
UEA
University of East Anglia
University of Bradford
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University of Leicester
University of Kent
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University of Oxford
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