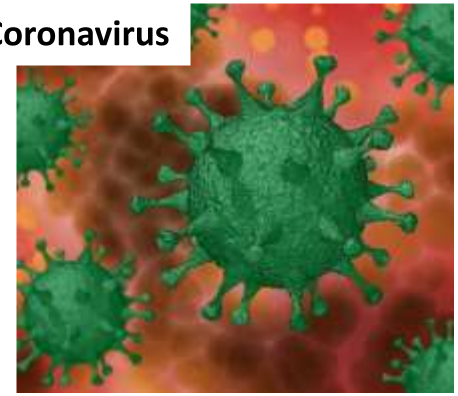
University of BRISTOL

University of BRISTOL

Coronavirus



FOSSIL VIRUSES

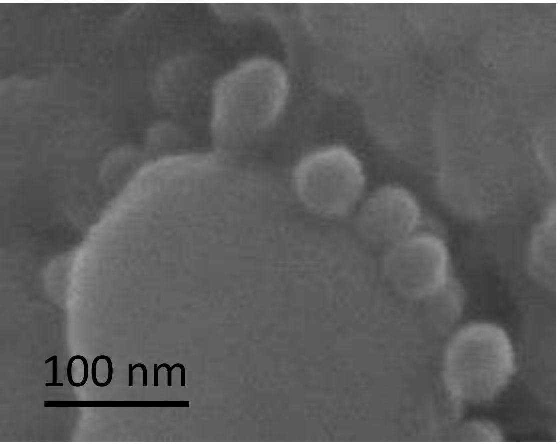
Cow Pea virus

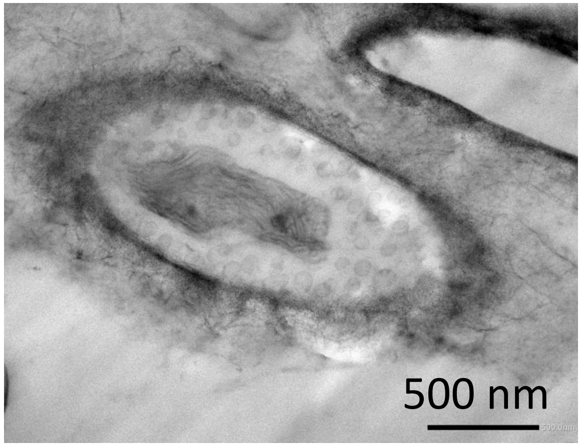
Maurice Tucker

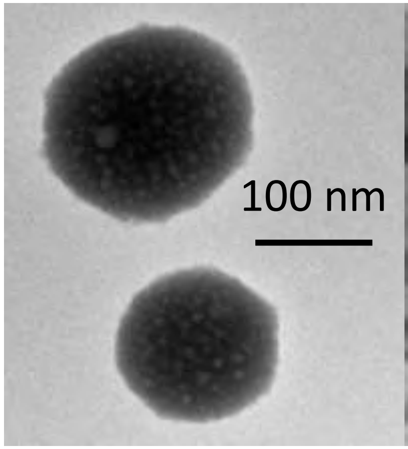
A current research project with colleagues:

Mirek Słowakiewicz, Andrzej Borkowski, Edoardo Perri, Marcin Syczewski, Filip Owczarek, Anna Sikora, Anna Detman, Fiona Whitaker, Ida Perrotta, Leon Bowen, Lisa Thomas

(Bristol, Warsaw, Krakow, Calabria, Durham, Bath Spa)







Viruses on a bacterium **Viruses in a bacterium**
in a modern microbial mat from Qatar

Experimentally mineralised viruses

Palaeoproterozoic viruses

THIS TALK:

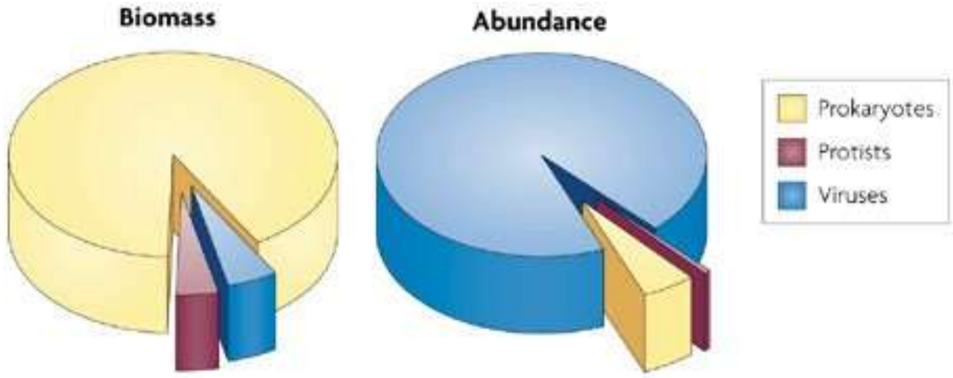
Viruses – an introduction
Bacteria and viruses (bacteriophages) and
viruses in microbial mats: their mineralisation, i.e. fossilisation
Experimental precipitation of minerals through viruses
Geological record of viruses
Viruses in natural environments: the good aspects …
Viruses in sedimentary processes: mineral precipitation
Viruses and extinction

VIRUSES: THE NEW FRONTIER IN GEOLOGY
DO THEY PLAY A ROLE ?

VIRUSES

Viruses are everywhere, in greater abundance than bacteria.

In seawater 10 billion per ml, 10-100x more than bacteria.



Viruses, Prokaryotes, Protists in seawater
Suttle 2007

Nature Reviews | Microbiology

A gram of soil may contain 10 billion bacteria in the vicinity of plant roots
BUT
the number of viruses is 10 or more times these figures.
In terms of numbers, viruses are the most abundant biological entities on Earth.

Viruses occur in sediments, like bacteria, shallow and deep, and all environments; hot springs and ice-cold glaciers, the deep subsurface, rain (and Mars, Venus ?!). In terms of volume or mass, however, viruses constitute a much smaller amount than bacteria, just a few %.
AND IN US TOO: For example, the weight of bacteria in the human body is estimated to be 200 gm; the weight of viruses would be less than 10 gm.
The number of viruses is around 380 trillion (= human virome).

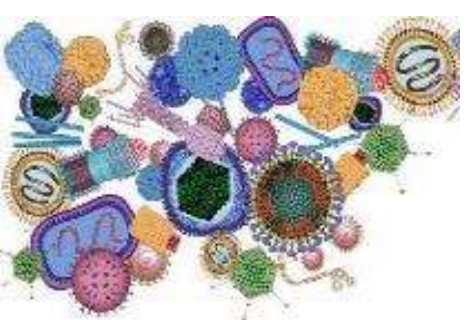
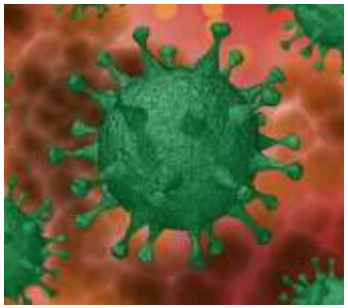
VIRUSES versus BACTERIA

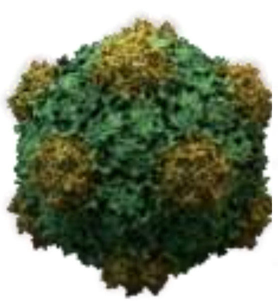
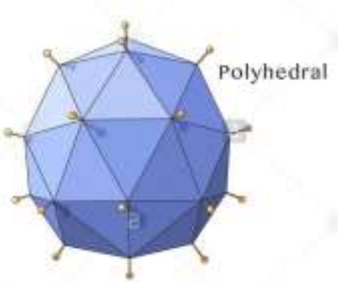
Viruses: 10s-100s nm diameter. Bacteria < micron to 10s of microns. Largest 750 µm.

Bacteria are single cells, prokaryote organisms (i.e. no nucleus), with cell wall within which cytoplasm containing DNA and organelles.
They mostly reproduce asexually by binary fission (dividing into 2 daughter cells).

Viruses are somewhere between living and non-living organisms. They consist of a protein shell (called a capsid) within which there is nucleic acid (i.e. RNA or DNA) which carries genetic information. Some viruses have an outer membrane (an envelope) which may be spikey, as in a coronavirus.

Virus shapes: spheroidal, rod-shaped or helical (spiral).
Many symmetrical with an icosahedral shape, i.e. spheroidal with sides or faces, like an old-fashioned football. Some viruses have a 'tail'.

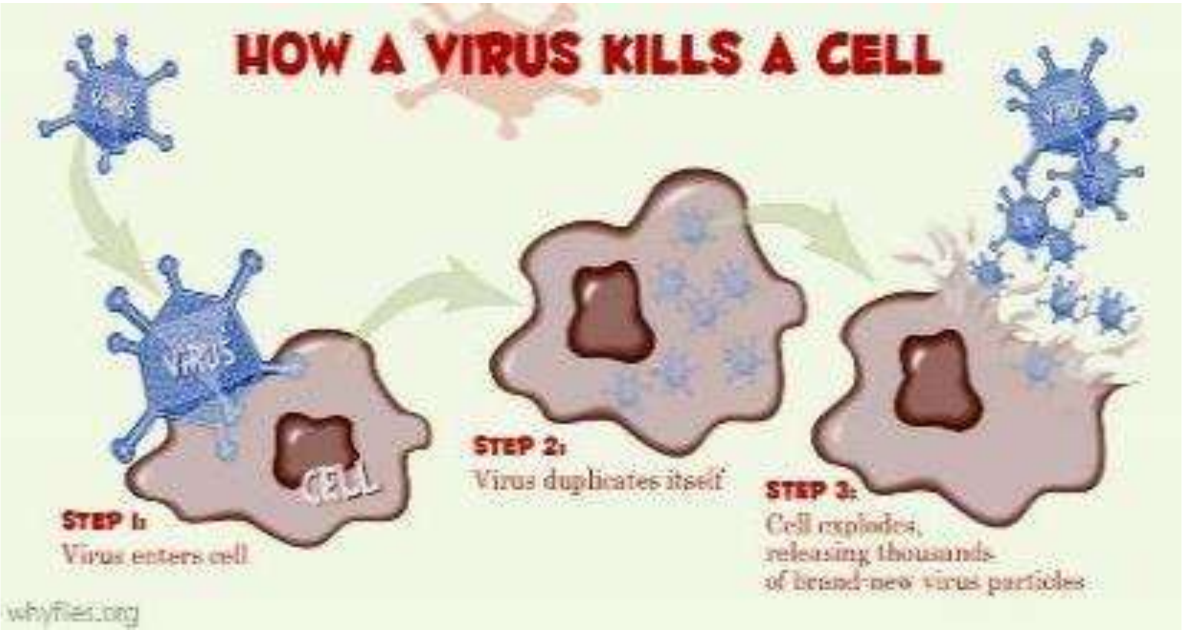



VIRUSES

Viruses are dependent solely on a suitable host for replication; hence they are frequently referred to as *obligate intracellular parasites*.

Simple biological entities, indeed are they actually living organisms ?
They only reproduce in host cells.
Viral DNA enters the cell; new viruses form; they multiply and burst out (lysis), and they may then infect other bacteria/cells.
Viruses closely associated with bacteria called bacteriophages or just phages.
Viruses (like EPS, i.e. extracellular polymeric substances) have a negative charge (from hydroxyl and carboxyl functional groups), so can attract cations.

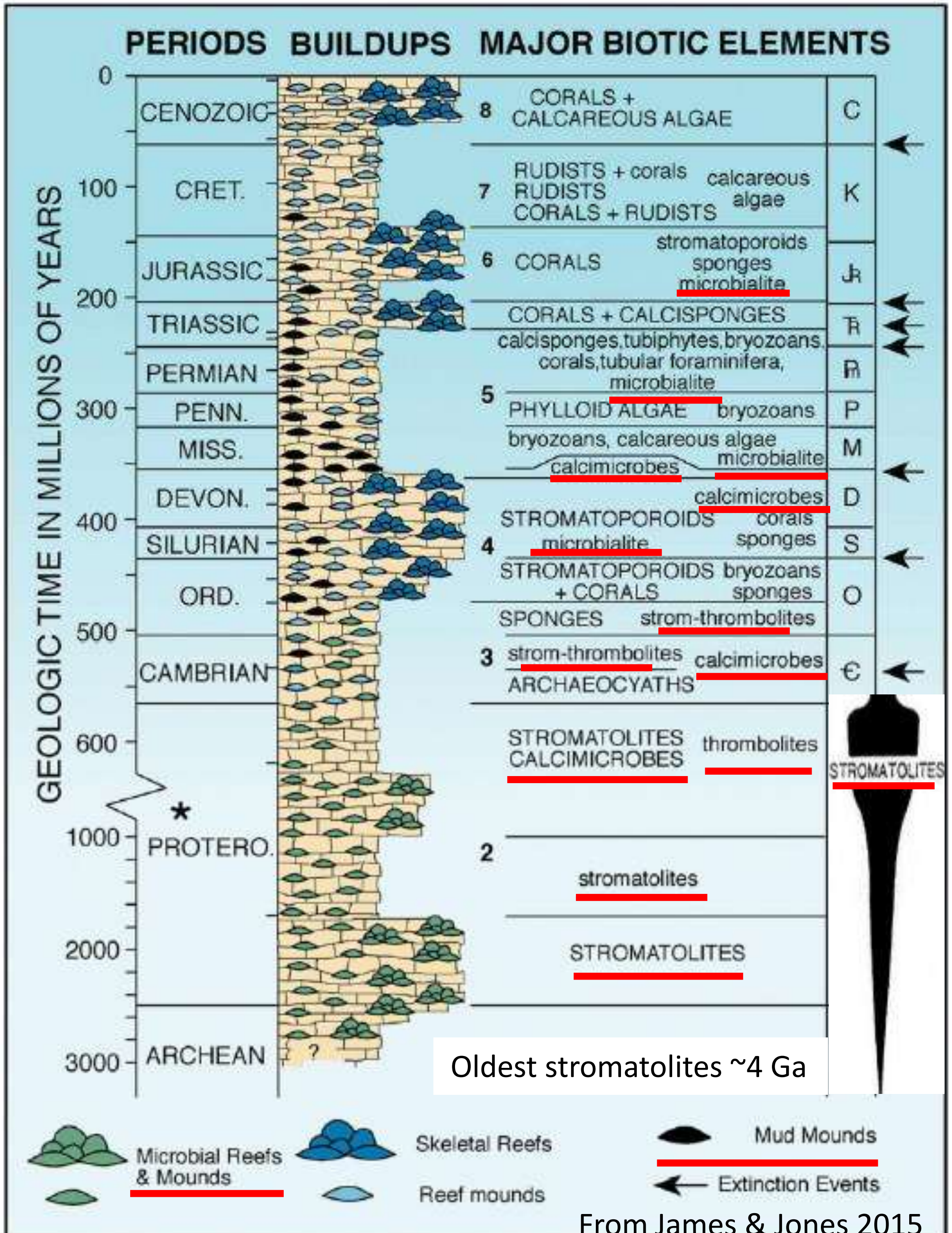


The close association of viruses with bacteria is well documented in microbial mats – where many more viruses than bacteria.

Microbialites occur throughout the stratigraphic record.

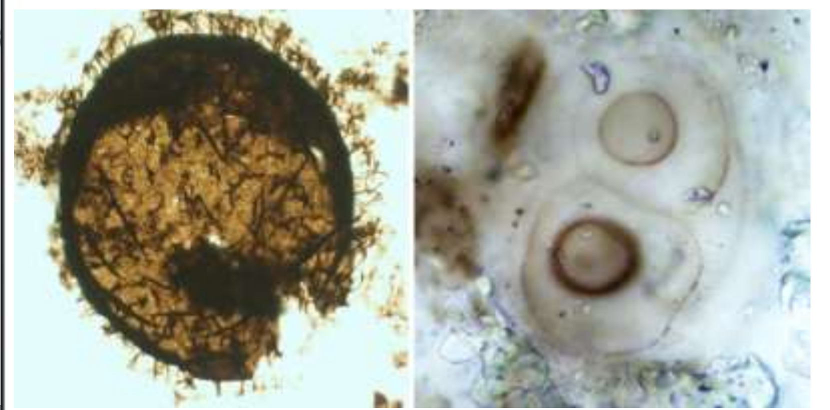
CARBONATES THROUGH TIME

Microbial carbonates from the early Archean



Donoghue 2020

Fossil bacteria (or pseudofossils?) Archean (3.4 Ga) Apex Chert, WA.

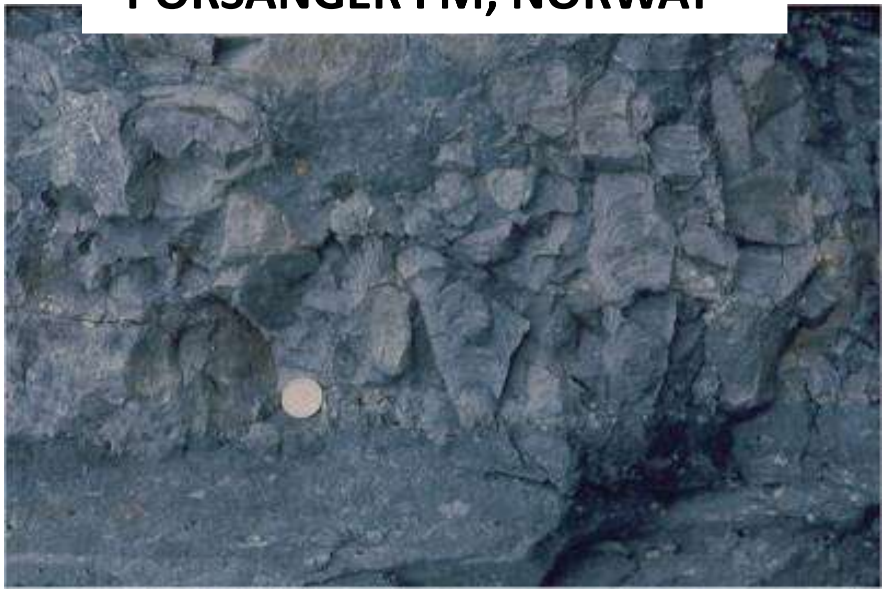


Eukaryote cells + nuclei. Ruyang, China (1.8 Ga) and Bitter Springs, Oz (1 Ga).

MODERN STROMATOLITES

PRECAMBRIAN STROMATOLITES

NEOPROTEROZOIC (1000 Ma) PORSANGER FM, NORWAY



Stromatolite reef and oolite banks

Peritidal microbial facies (Tucker 1976, 77)

MICROBIALITES NEARBY

Cotham Marble ('landscape marble')
Rhaetic, Triassic, Bristol District

Purbeck – Lulworth
Fossil Forest
(BGS fieldtrip 2017)

Also microbialites (stromatolites) in the Carboniferous (Clifton Down Limestone)

MICROBIAL MATS and STROMATOLITES

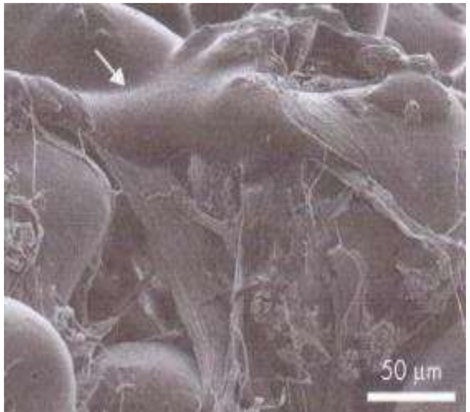
Microbial mats consist of cyanobacteria, other bacteria (SRB), archaea and green algae, plus fungi, diatoms, **EPS** (extracellular polymeric substances, ‘mucilage’) and **viruses,** all forming a **BIOFILM.**

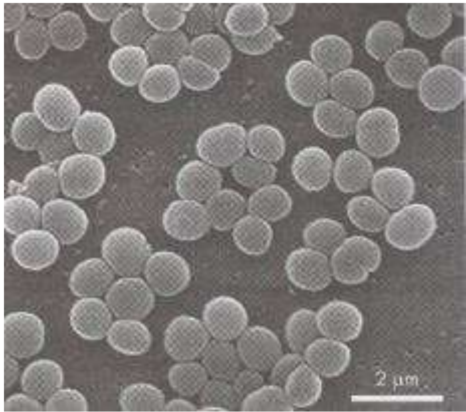
Microbial precipitates common in mats plus sediment trapped and bound into the mat by the biofilm/EPS and filaments.

Microbes induce precipitation through extraction of CO_2 (in HCO_3^-) from water through **photosynthesis (**+ other processes).

ALSO: tufa and travertine (springs)
and
planktic microbes with EPS and viruses.

Coccoid and filamentous cyanobacteria
and EPSs (extracellular polymeric substances)

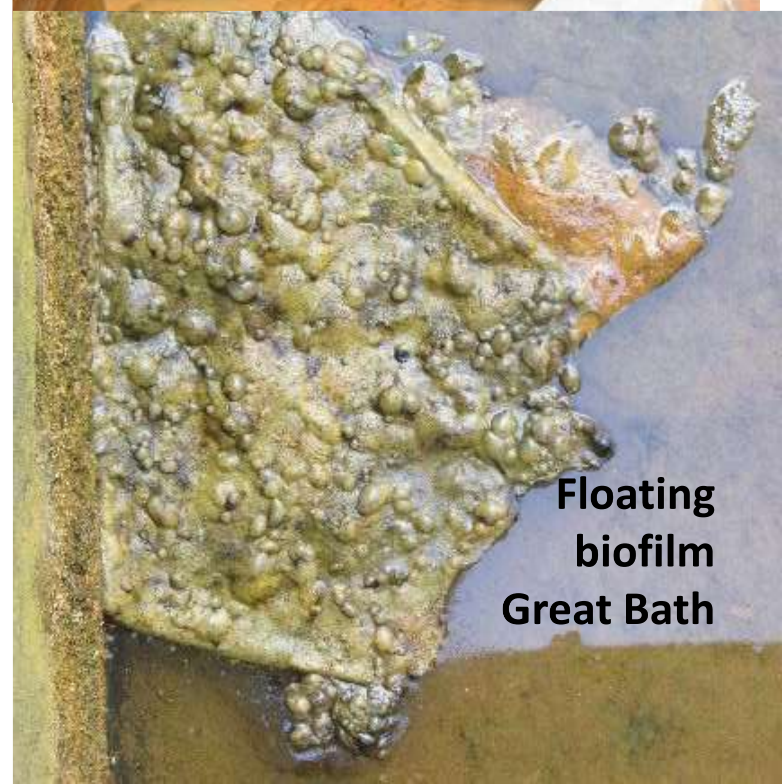




If you want to see biofilms and microbial mats – go to the Roman Baths:

Mats and biofilm Sacred Spring / King's Bath

Mat/ biofilm edge of Great Bath

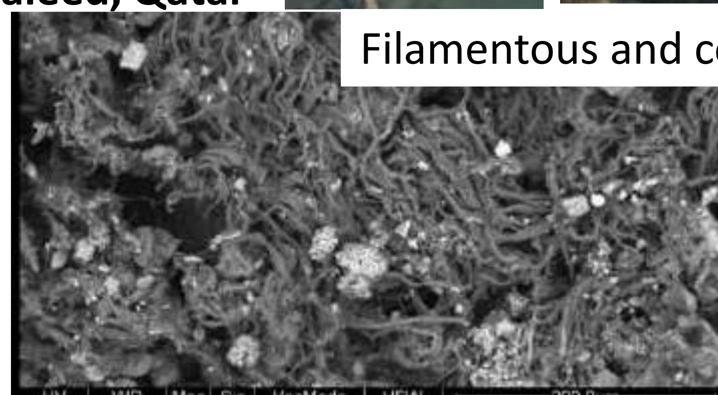


Floating biofilm Great Bath

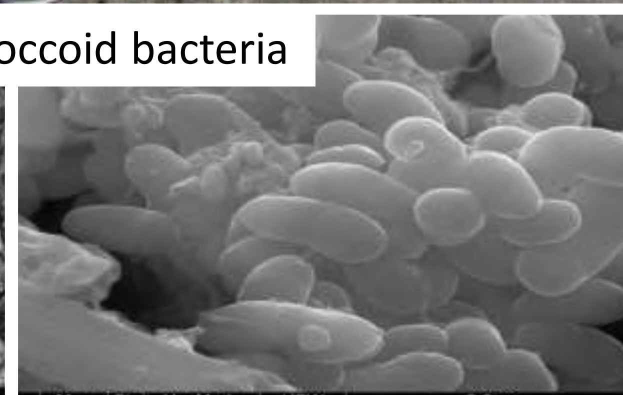
MICROBIAL MATS, QATAR

roles of EPS (mucilage), bacteria and viruses in mineral precipitation and HC source-rock potential

Microbial mats at Mesaieed, Qatar



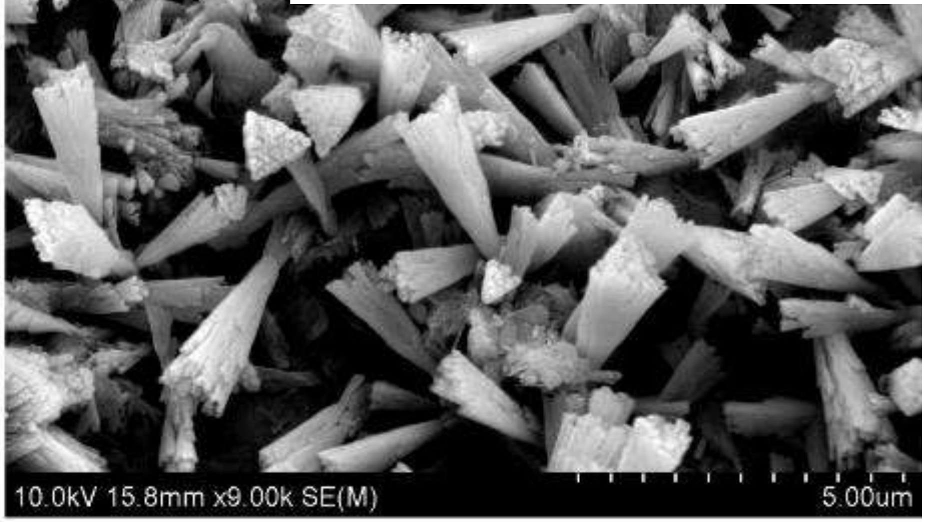
Filamentous and coccoid bacteria

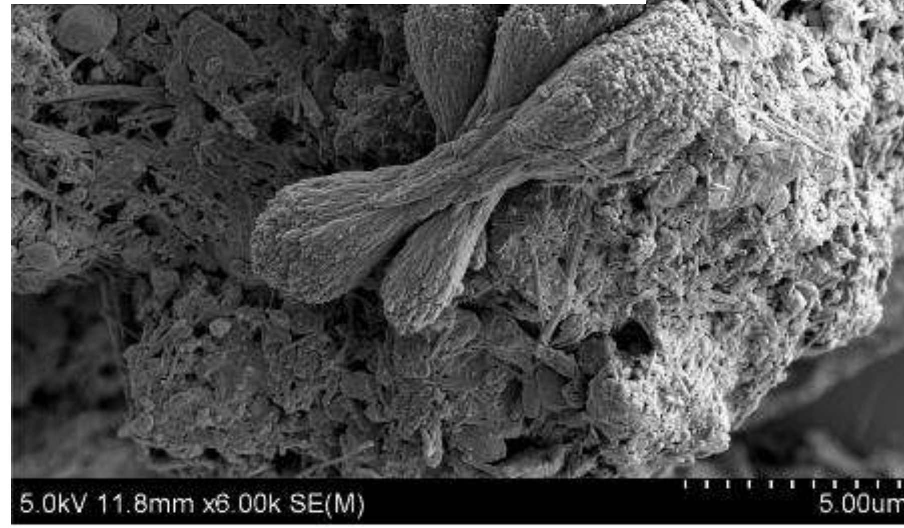


Biomarker study: Slowakiewicz, Tucker, Whitaker et al. (2016) *Organic Geochemistry*

Mineral precipitates in mats: Perri, Tucker, Slovakiewicz et al. (2018) *Sedimentology*.

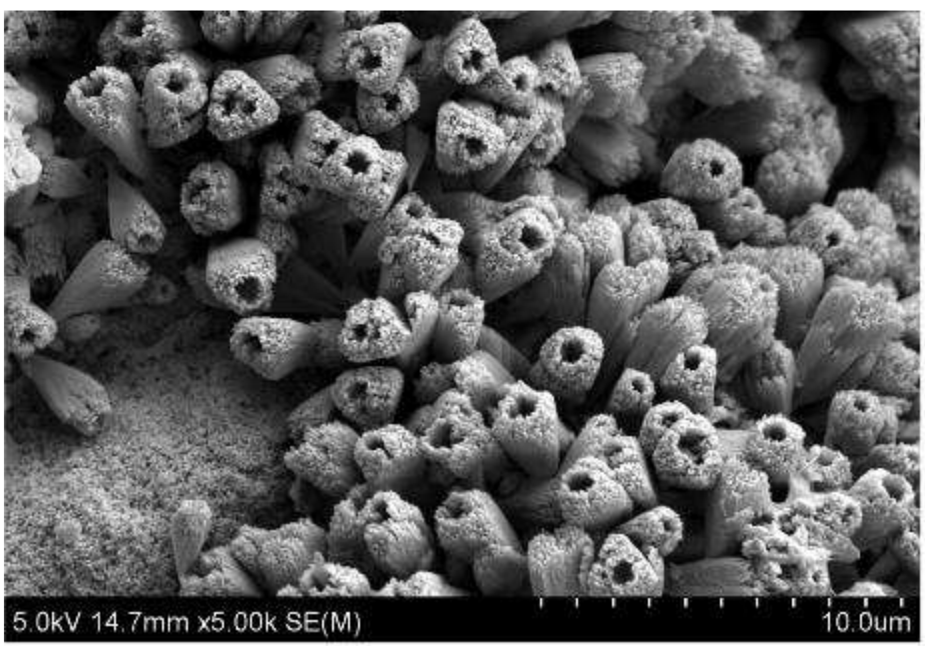
MINERALS PRECIPITATED IN MICROBIAL MATS

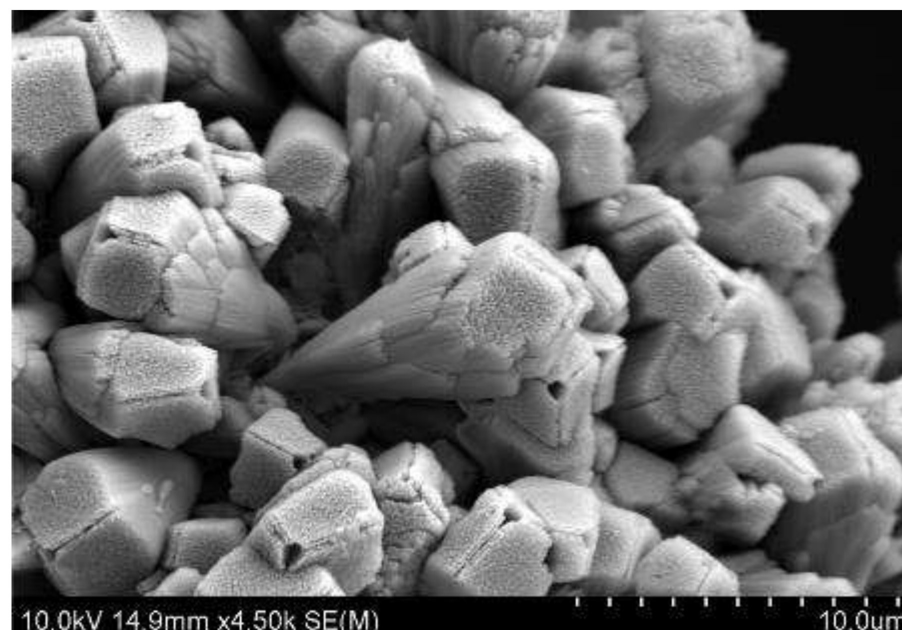


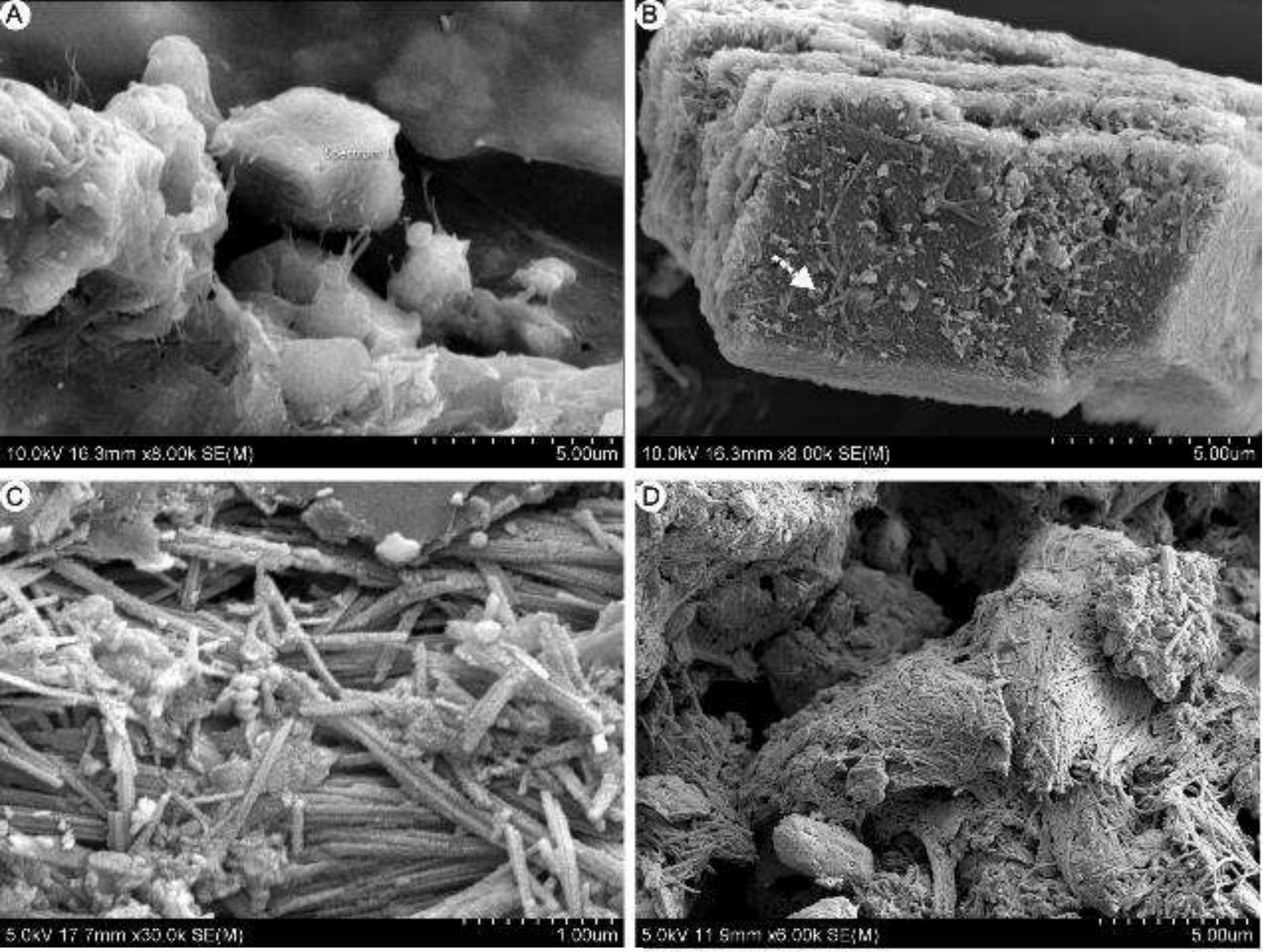


CALCITE CRYSTALLITE BUNDLES TO CRYSTALS

Perri, Tucker, Slovakiewicz et al. (2018) *Sedimentology*.







ALSO PRESENT:

VHMC-DOLOMITE

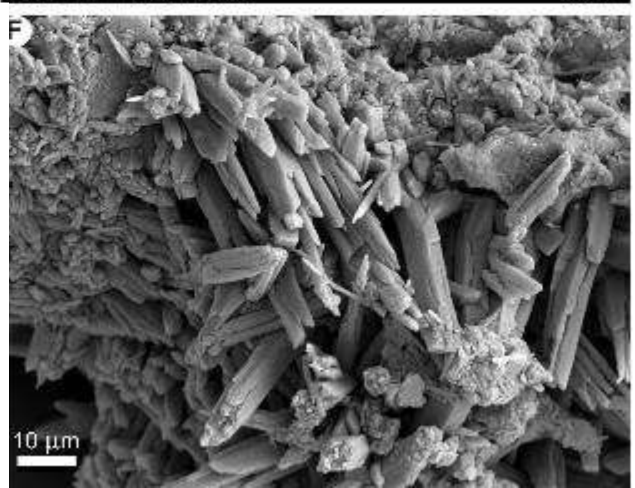
rhombs (A, B)

PALYGORSKITE (C, E)

Clay fibres Mg 8.5%, Al 1.9 %, Si 8.4%, Ca 5.4% O 61.7 %. Felted mat of clay fibres (?permineralised EPS).

ARAGONITE (F)

needles

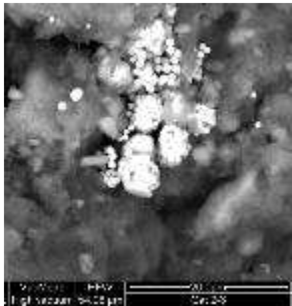


MINERAL PRECIPITATION THROUGH MICROBIAL PROCESSES

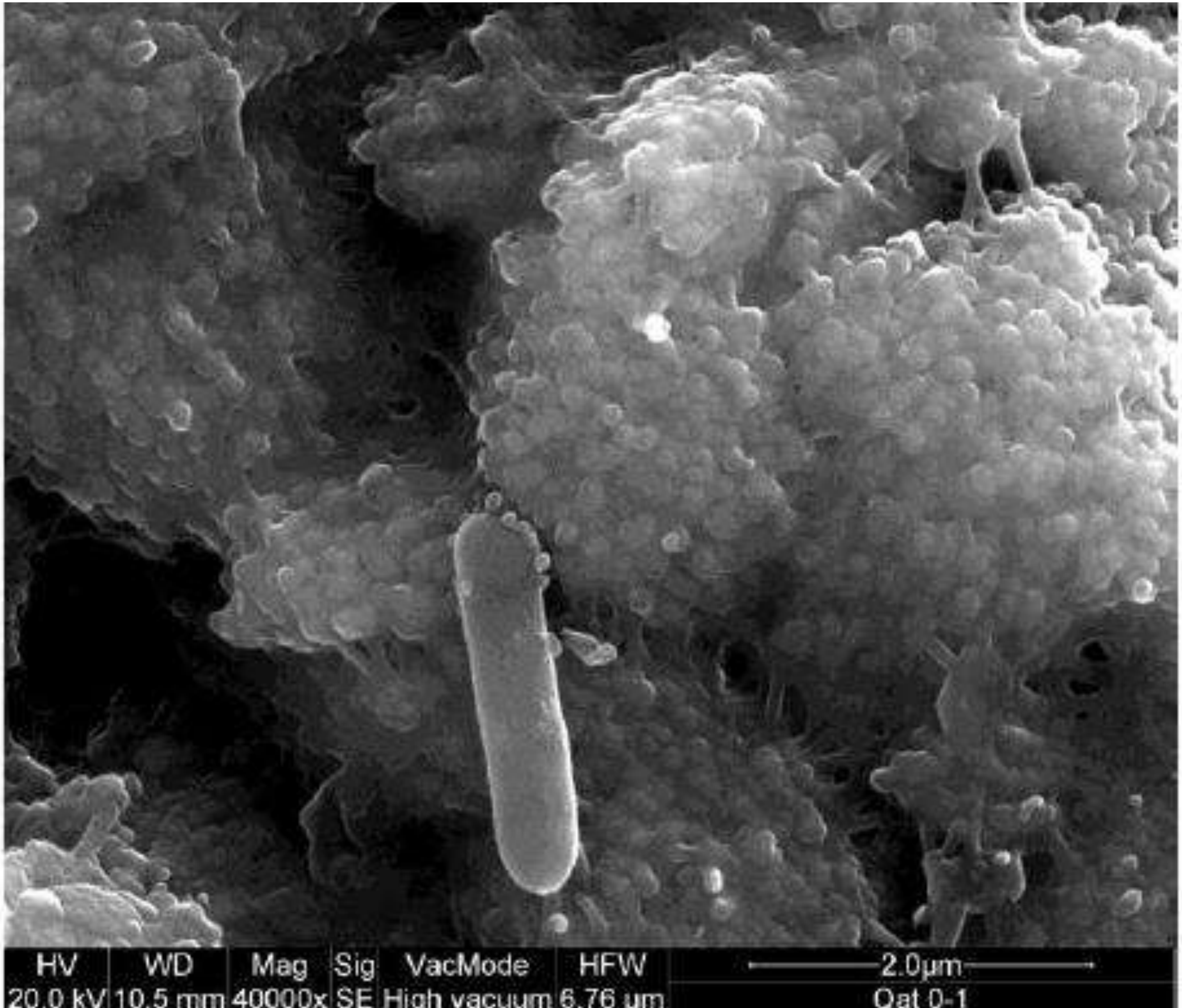
BUT HOW CRYSTALS NUCLEATED ?

AND PYRITE

Perri, Tucker, Slovak. et al. (2018) *Sedimentology*.



SEM: NANOSPHERES IN UPPER MM OF MICROBIAL MAT



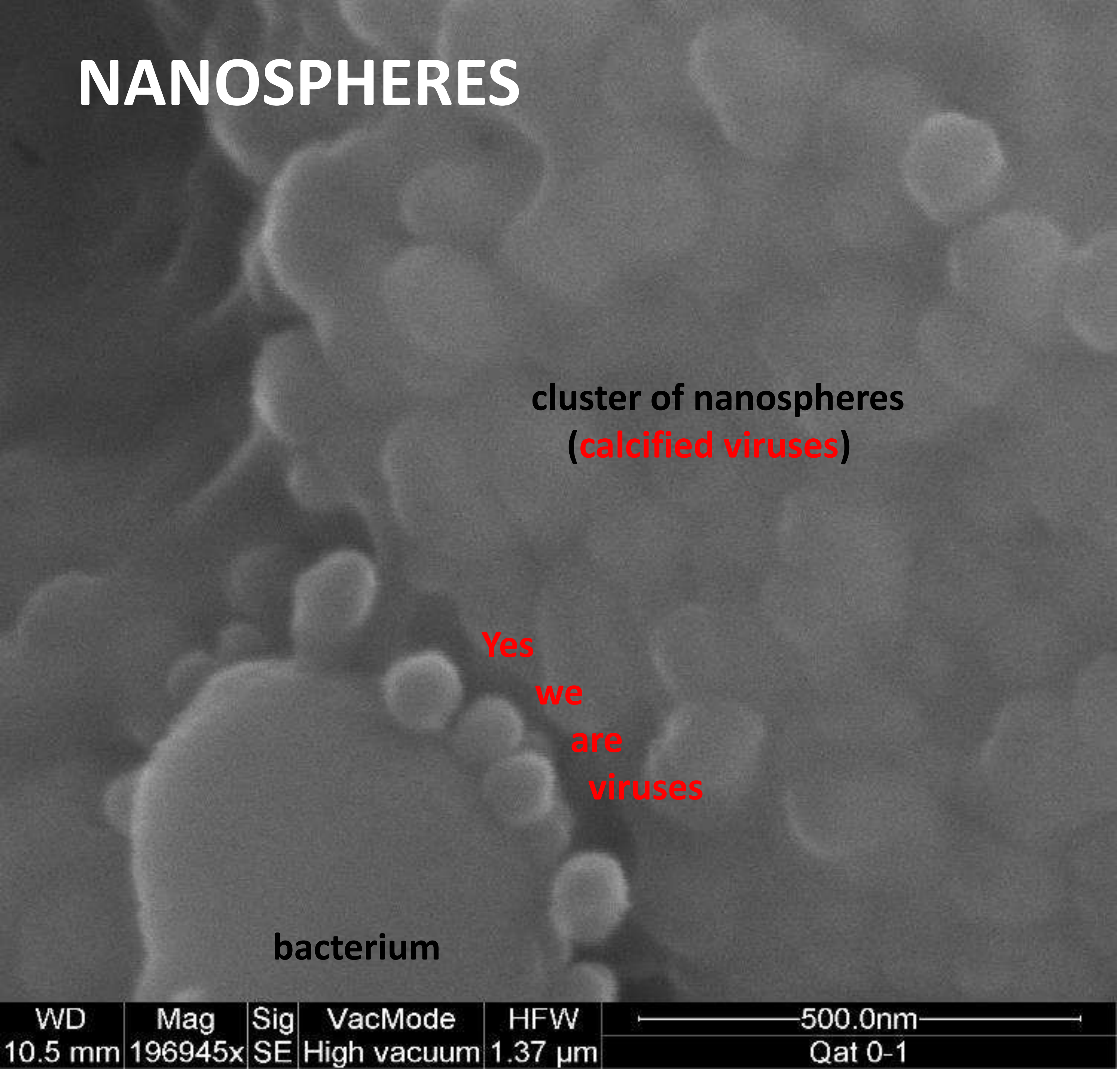
Nanospheres enveloped in EPSs forming clusters, i.e. peloids, and attached to bacterium.

Uniform size: ~100 nm. Notice shape.

Are these viruses ?

Other possible origins – bacterial vesicles or intracellular precipitates or abiotic.

NANOSPHERES



Nanospheres attached to bacterium and in a cluster, where they appear to amalgamate into larger features.

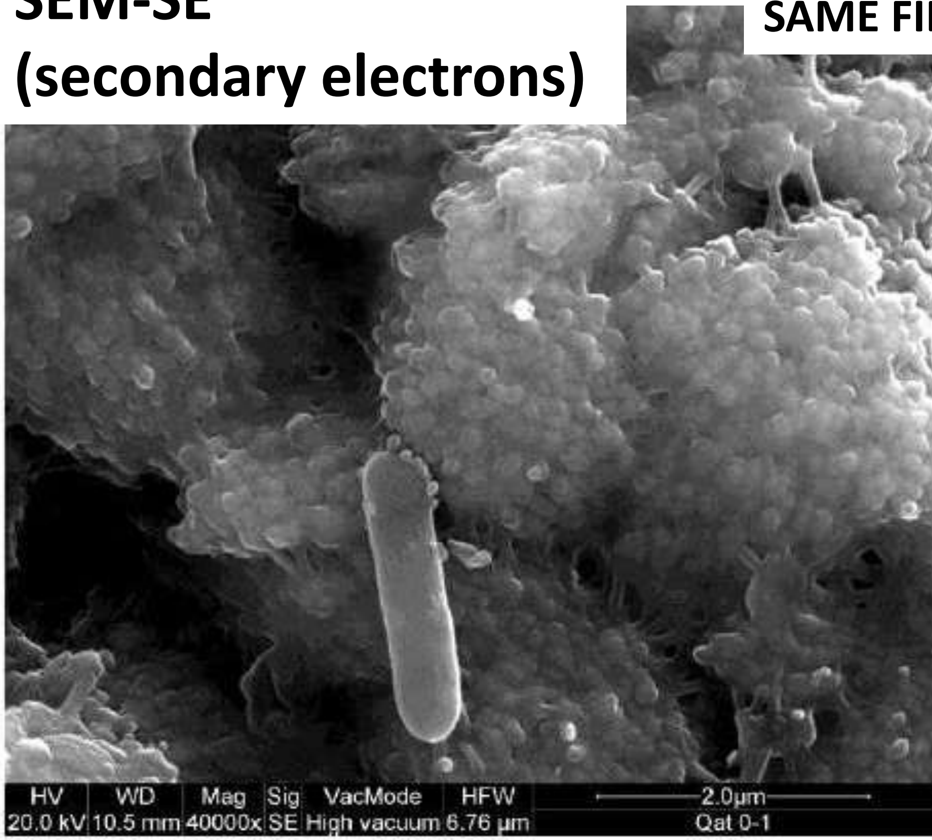
Notice shape: icosahedral, and similar size. Very likely to be viruses caught in the act of infecting.

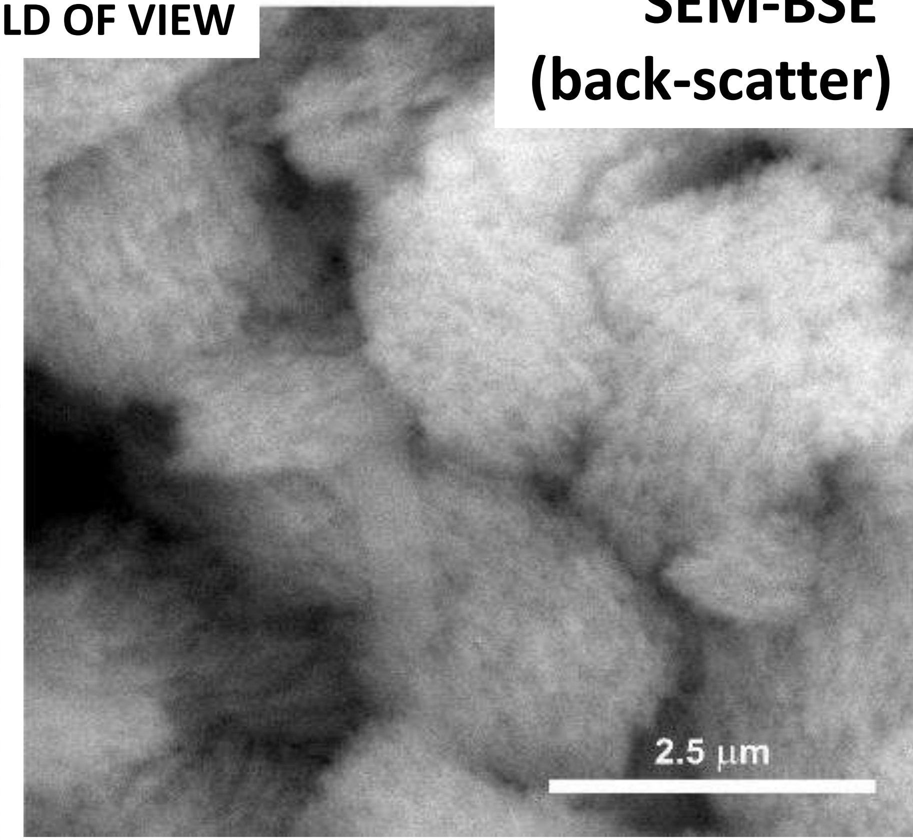
NANOSPHERES IN UPPER MM OF THE MICROBIAL MAT

SEM-SE (secondary electrons)

SAME FIELD OF VIEW

SEM-BSE (back-scatter)





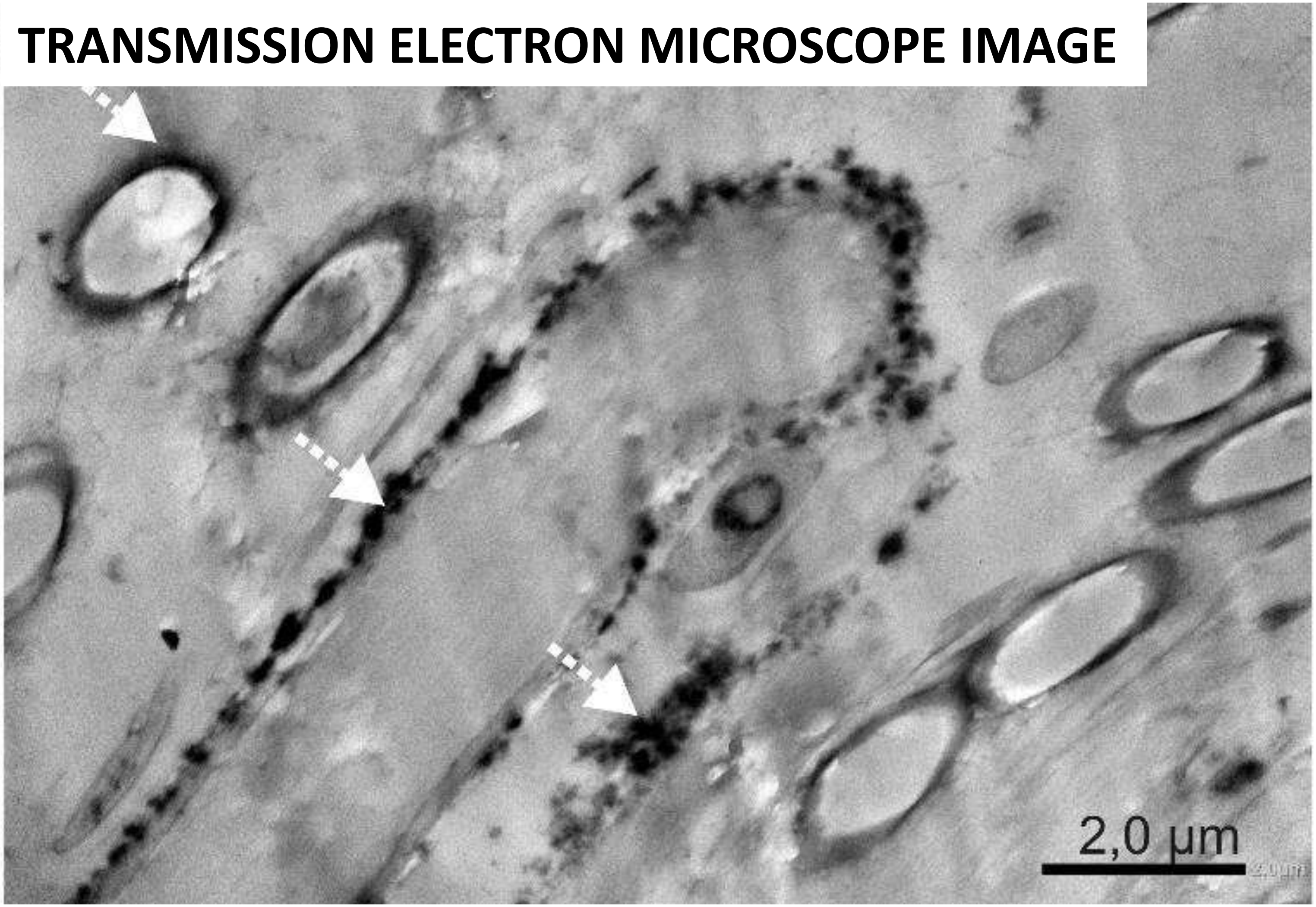
With BSE, organic matter (EPSs, bacteria) almost transparent (low atomic no. C,H,O), but where higher atomic no. elements (Ca, Mg, Si, Fe) see a lighter shade.

i.e. THEY ARE PER-MINERALISED

Nanospheres in clusters composed of nanocrystallite mineral bundles (=peloids)

BUT NOTE bacterium and attached viruses not permineralised (yet).

TRANSMISSION ELECTRON MICROSCOPE IMAGE

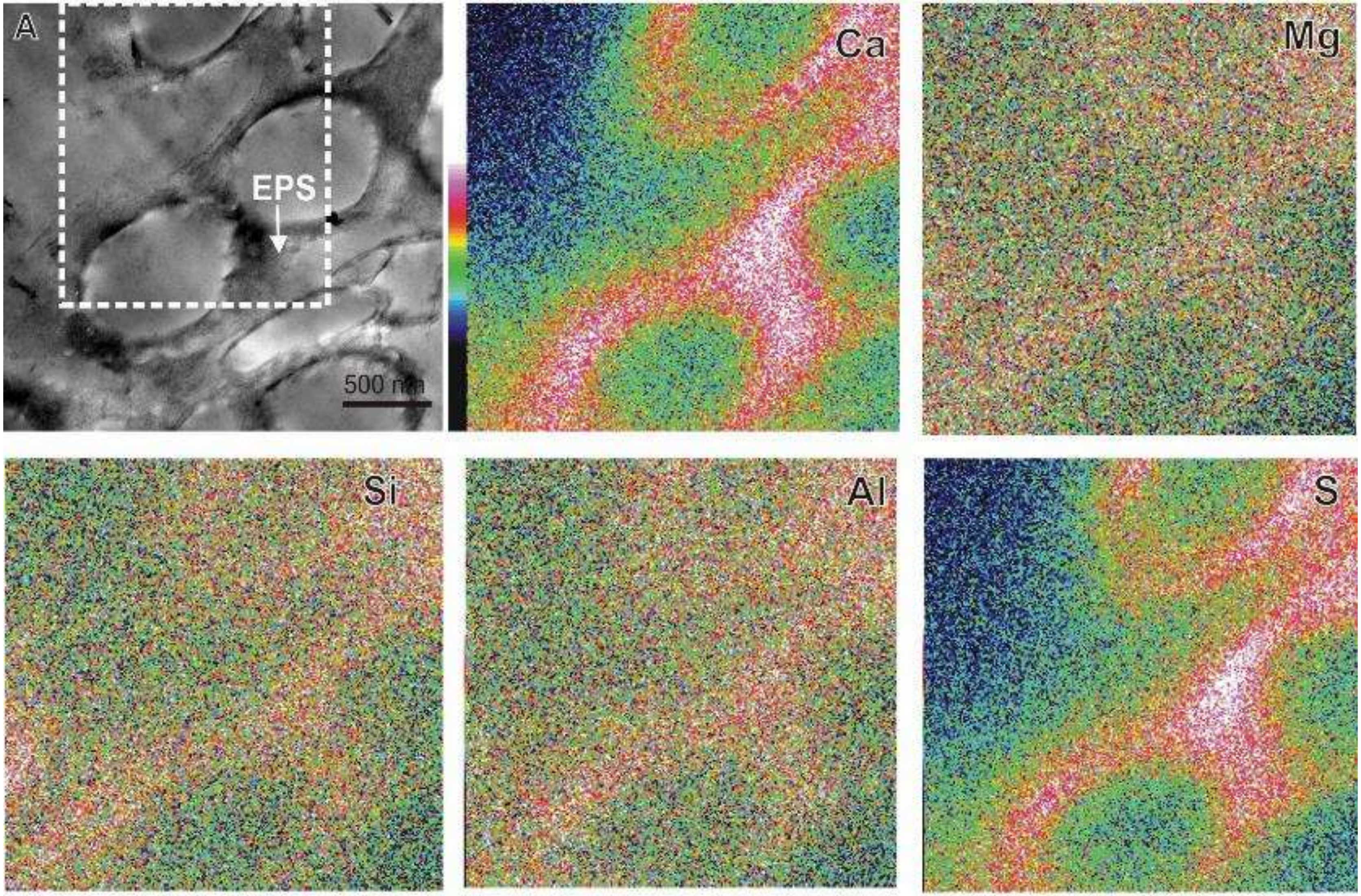


With TEM, electron-dense / darker areas (dashed arrows) = minerals. Shows early stage of mineral formation with initial sites of nucleation within the EPS that surround the bacterial cells.

SO - ARE THESE MINERALISED VIRUSES ?

Top mm of microbial mat, Mesaieed, Qatar.

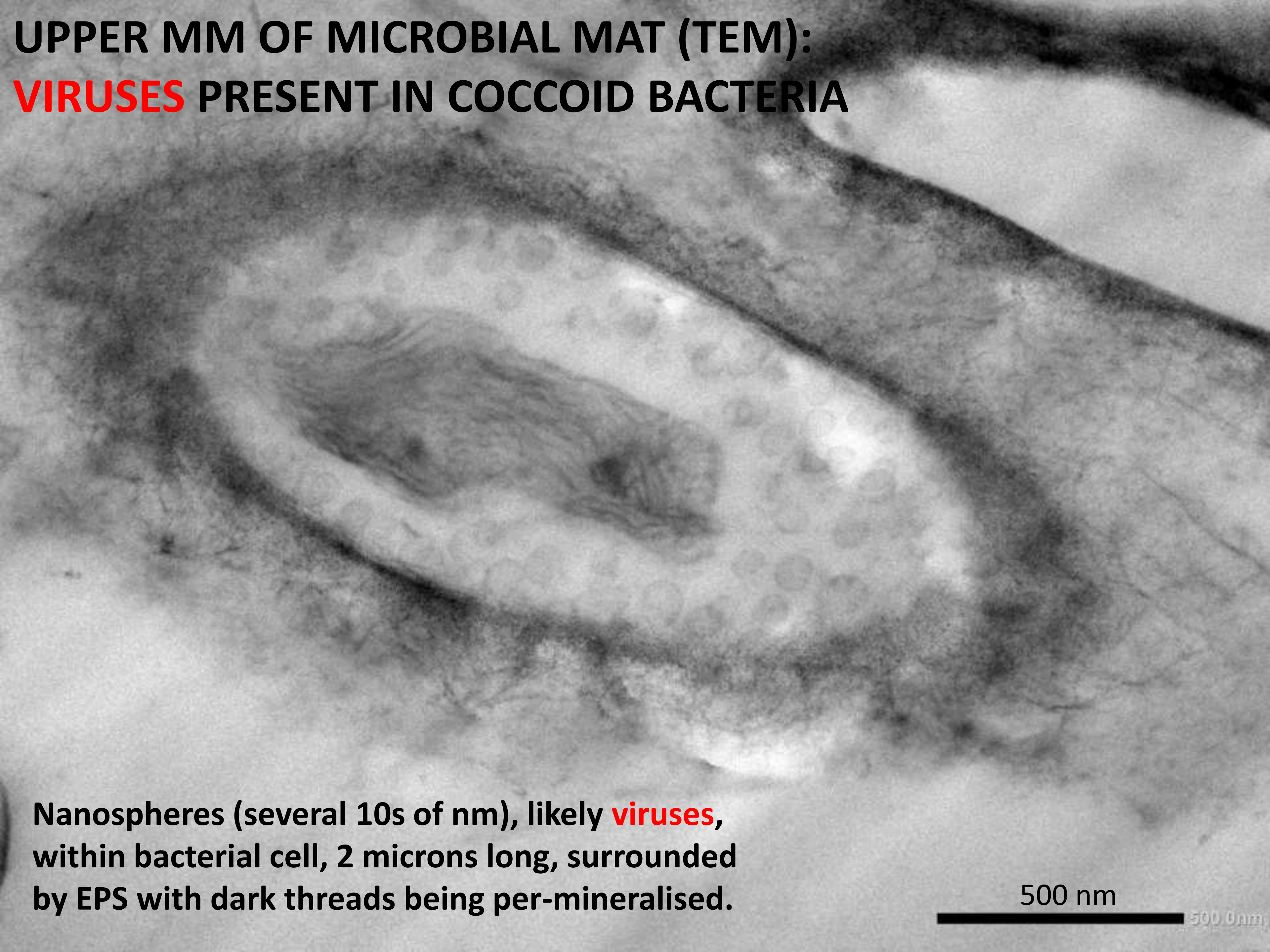
COMPOSITION OF AMORPHOUS MINERAL PRECIPITATES IN EPS



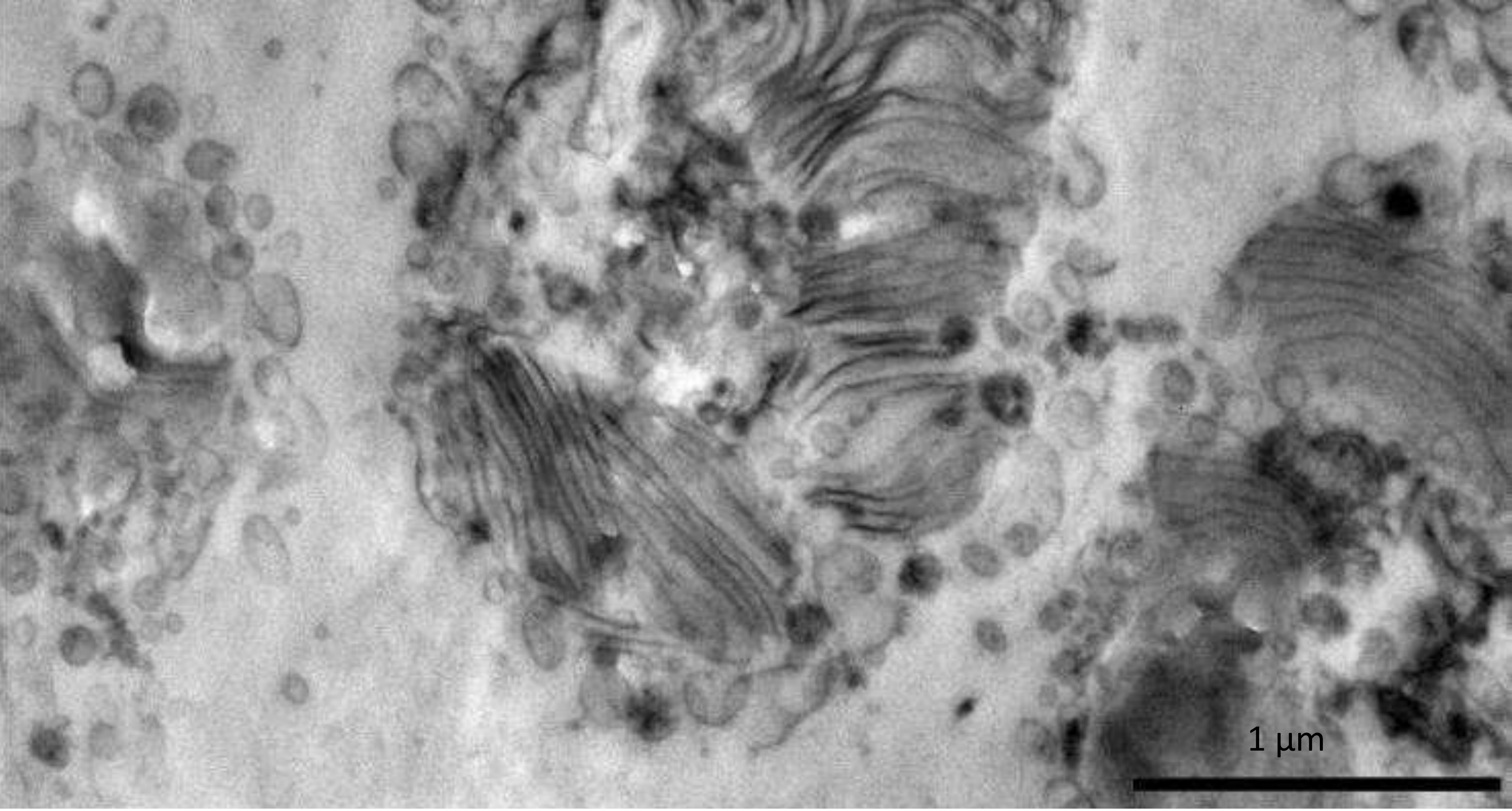
Elemental compositional maps of EPS around coccoid bacterial cellsbeing mineralised: Ca, Mg, Si, Al, S..

C, O and N are not shown but form 95-98 % of the total element composition.

UPPER MM OF MICROBIAL MAT (TEM): VIRUSES PRESENT IN COCCOID BACTERIA



Nanospheres (several 10s of nm), likely viruses, within bacterial cell, 2 microns long, surrounded by EPS with dark threads being per-mineralised.

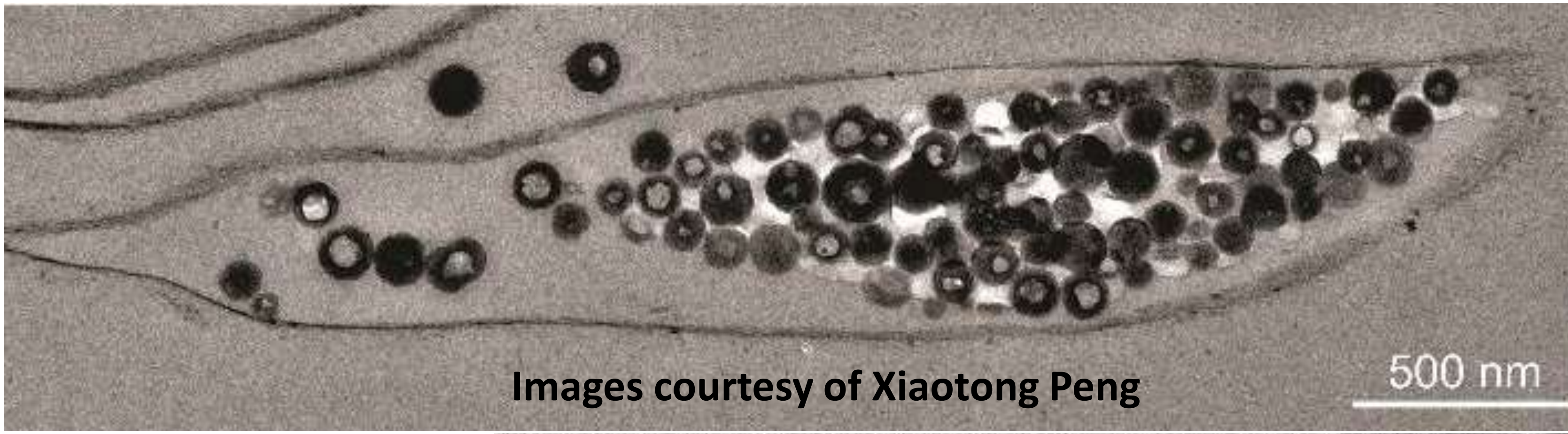


THUS: Nanospheres – which we interpret as viruses - are becoming per-mineralised. Here seen within and *between* bacteria (with thylakoids – photosynthetic apparatus).

Mineralised viruses i.e. FOSSILISED VIRUSES

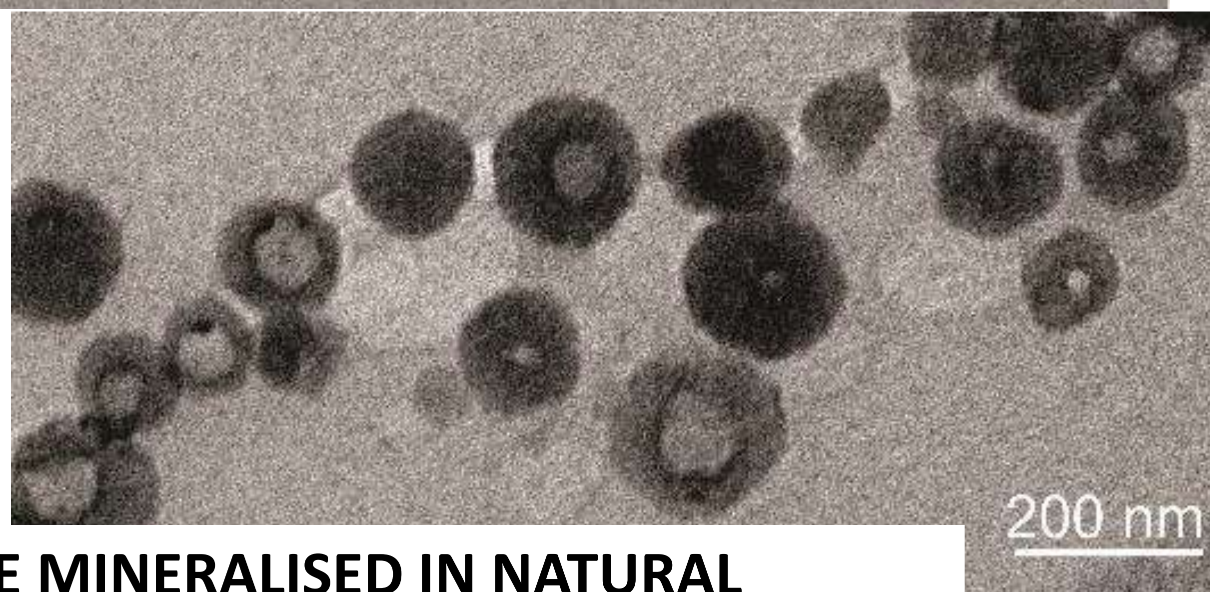
Permineralised viruses also reported by Pacton et al. 2014, 2015, and De Wit et al. 2015.

VIRUSES ALSO BEING MINERALISED IN HOT SPRINGS



Here viruses in a bacterium being mineralised and coated by silica.

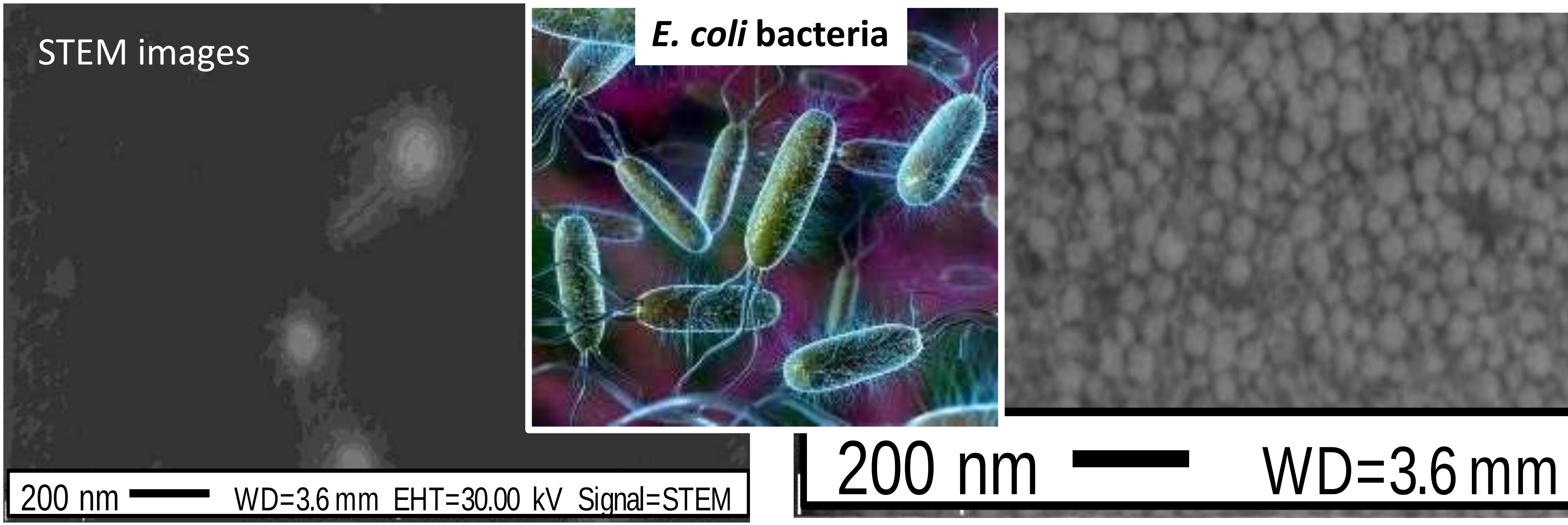
Sinter, hot spring in China
Peng & Jones (2013)



THUS VIRUSES CAN BE MINERALISED IN NATURAL ENVIRONMENTS, THAT IS FOSSILISED – NOW SOME EXPERIMENTS

OUR EXPERIMENTS WITH VIRUSES AND CARBONATE PRECIPITATION

Viruses (size 100 nm) extracted from *Escherichia coli* bacteria (size 1-5 µm)
***E. coli* common bacteria – in sewage, rivers, lakes, coasts… and stomachs !**

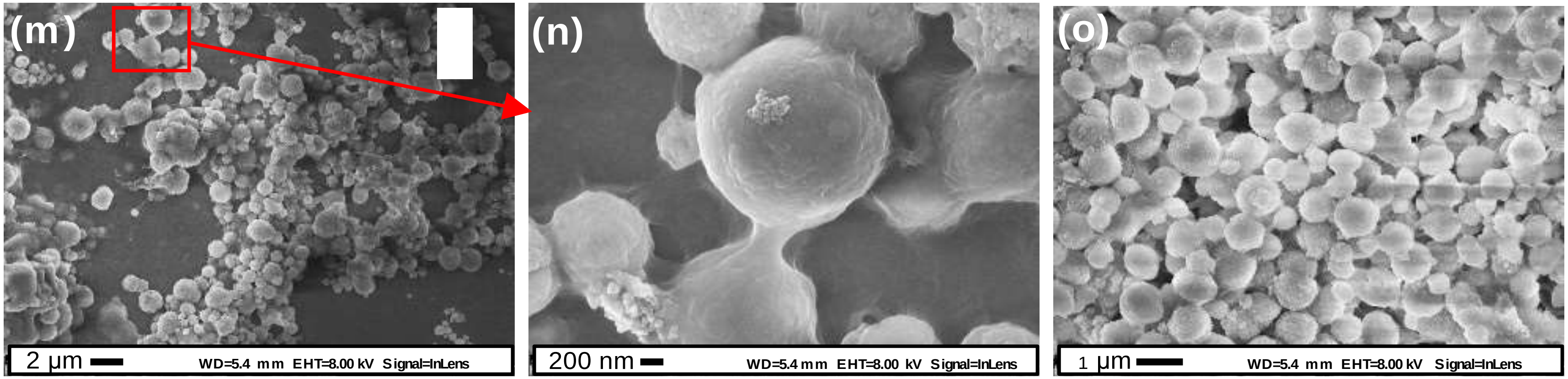


Before experiments: phage capsids +/- tails, often coalescing to form larger accumulations, with loose quasi-regular structure.

Experiments conducted by adding more and more Na_2CO_3 to $CaCl_2$ solution with a billion viruses per ml (also control experiments with no phages).

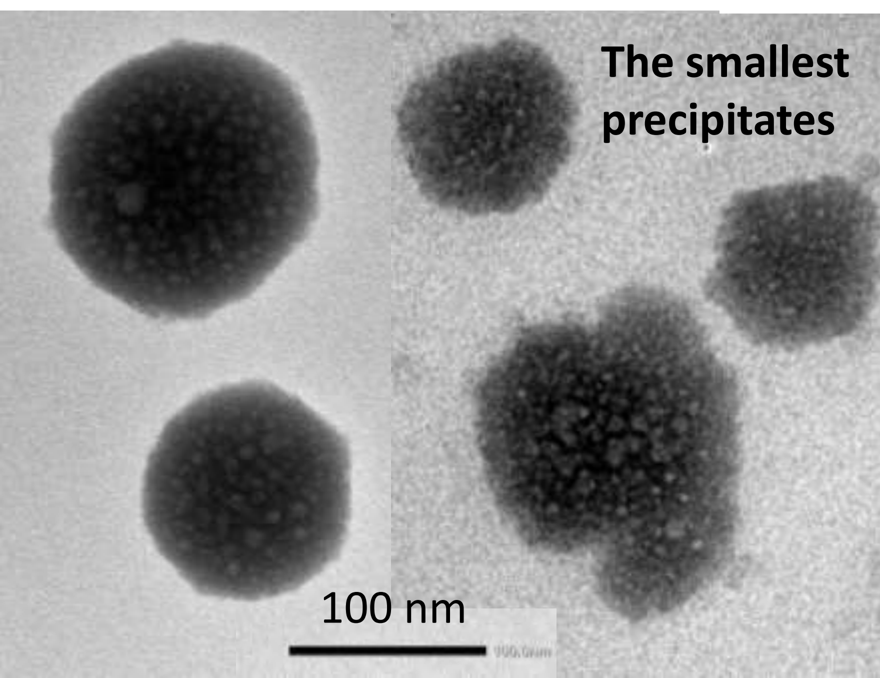
Results just published in *Geochim Cosmochim Acta* (Slovakiewicz et al. 2021).

phage concentration of 10^{11} mL^{-1}



PRECIPITATES OBTAINED DURING EXPERIMENTS WITH VIRUSES

we get nano-micro spheroids, dumbbells, tiny particles (80-100 nm) resembling permineralized capsids. Also coalescing of particles.



Control experiment precipitates only calcite, BUT with viruses: 70 % vaterite, 30 % calcite.

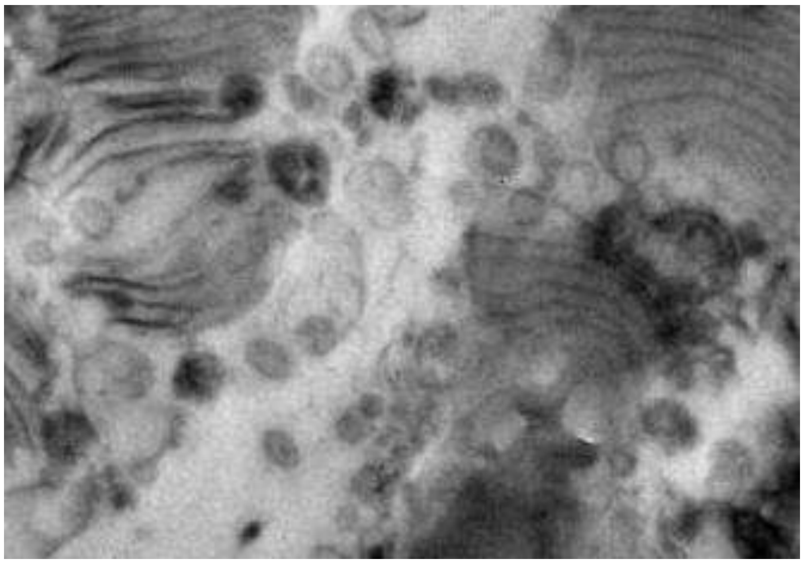
(vaterite unstable $CaCO_3$)

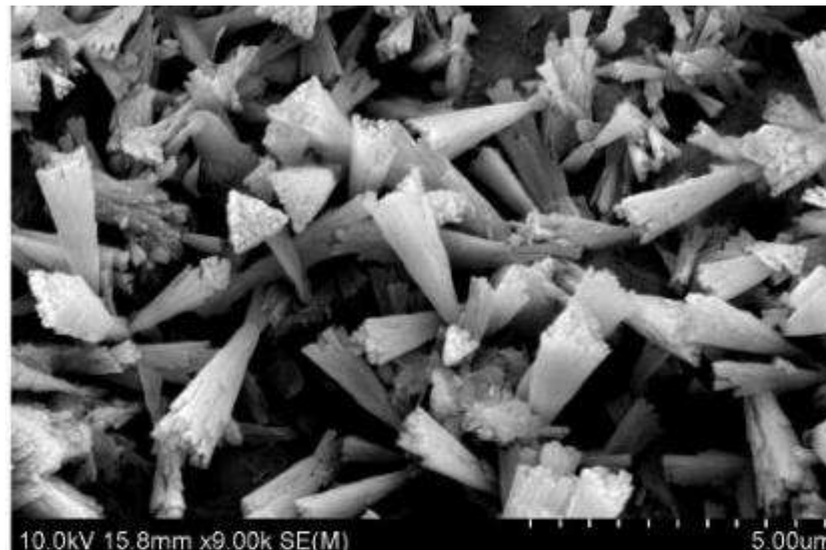
THUS VIRUSES DO HAVE AN INFLUENCE IN CARBONATE PRECIPITATION

in terms of crystal/particle size, shape, coalescence and mineralogy.

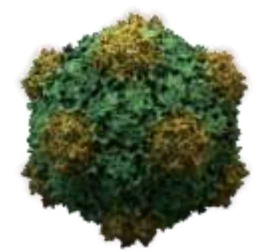
SO VIRUSES BEING MINERALISED AND THEY INFLUENCE CARBONATE PRECIPITATION.

WE SUGGEST THEY PROVIDE NUCLEI FOR FURTHER CARBONATE (& other) PRECIPITATION

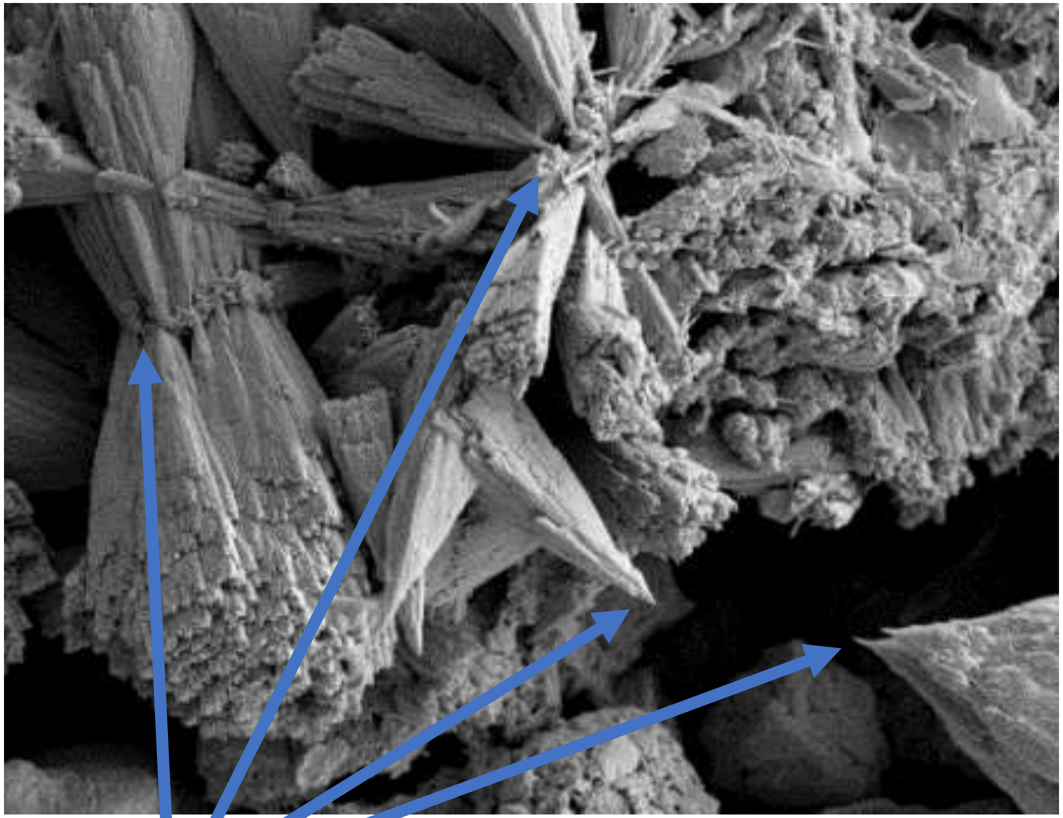




VIRUSES THE SEEDS FOR CRYSTAL GROWTH ?



HOW DO CRYSTALS GROW ?
HOW NUCLEATED ? SPONTANEOUS OR SEEDED ?

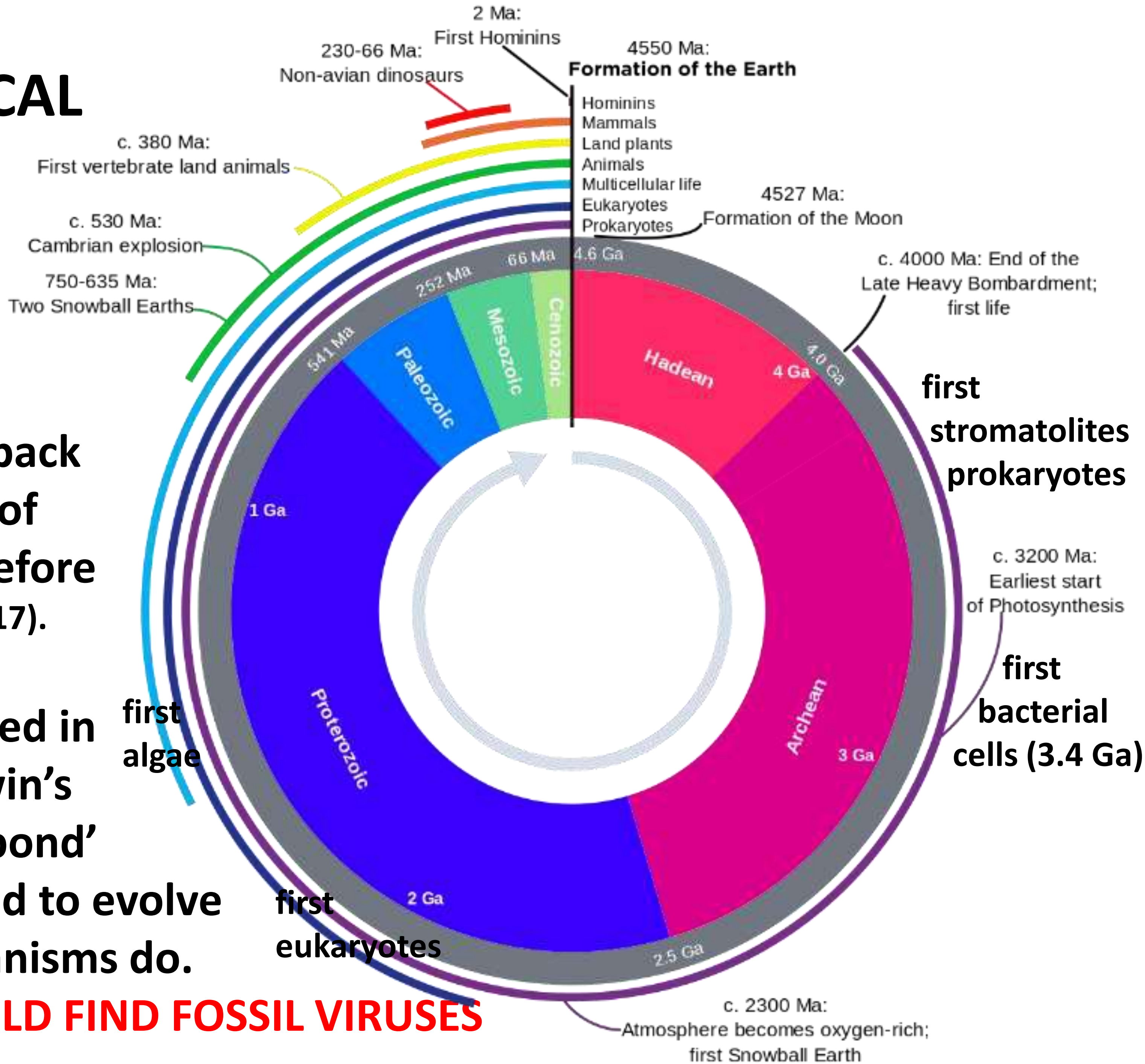


Can see nucleation / initiation points for calcite. But what started them off ?
Direct precipitation (*homogeneous/spontaneous nucleation*) not simple;
(some say impossible) seeds/nuclei are needed (that is *heterogenous nucleation*).

We suggest the initial precipitates are

MINERALISED VIRUSES (& EPS): THE NUCLEI FOR PRECIPITATION.

GEOLOGICAL RECORD OF LIFE

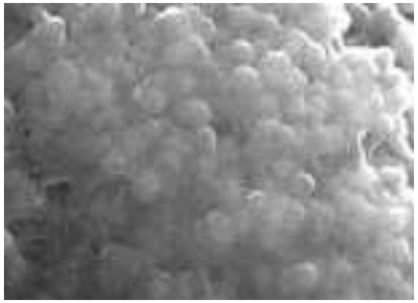
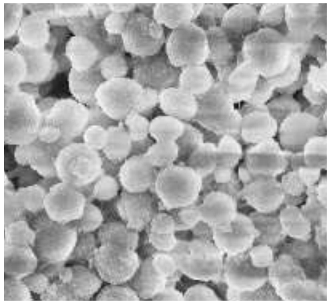


VIRUSES probably go back to the origin of life – if not before (e.g. Koonin 2017).

Viruses created in Charles Darwin's 'warm little pond' and continued to evolve as other organisms do.

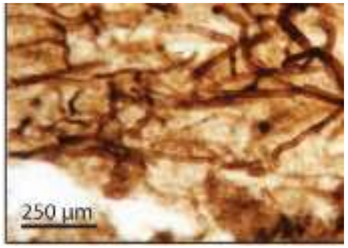
SO WE SHOULD FIND FOSSIL VIRUSES

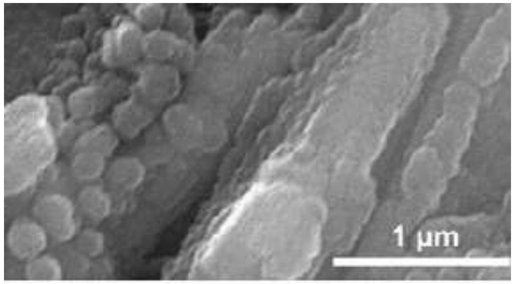
SO HOW ARE WE GOING TO RECOGNISE FOSSIL VIRUSES ?

SIZE: range 50-300 nm
BUT large numbers
all of a similar size

SHAPE: nanospheres, icosahedral, but there is a preservation issue: mineralised viruses may act as nuclei for further precipitation of the mineral fossilising them AND they coalesce

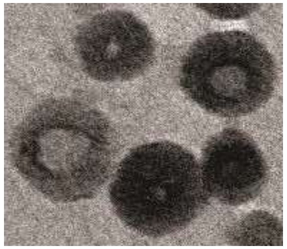




CONTEXT: associated with bacteria,
so look in stromatolites

MINERALOGY:

carbonate: calcite, aragonite, dolomite BUT recrystallisation and overgrowth, so may be difficult to recognize.



silica: resistant to recrystallisation, sinter, hot springs.

phosphate: lots of microbes, high nutrient supply.

iron minerals: BSR, suboxic-anoxic, siderite, ferrihydrite, pyrite

Viruses should be present throughout the geological record.

EXAMPLES

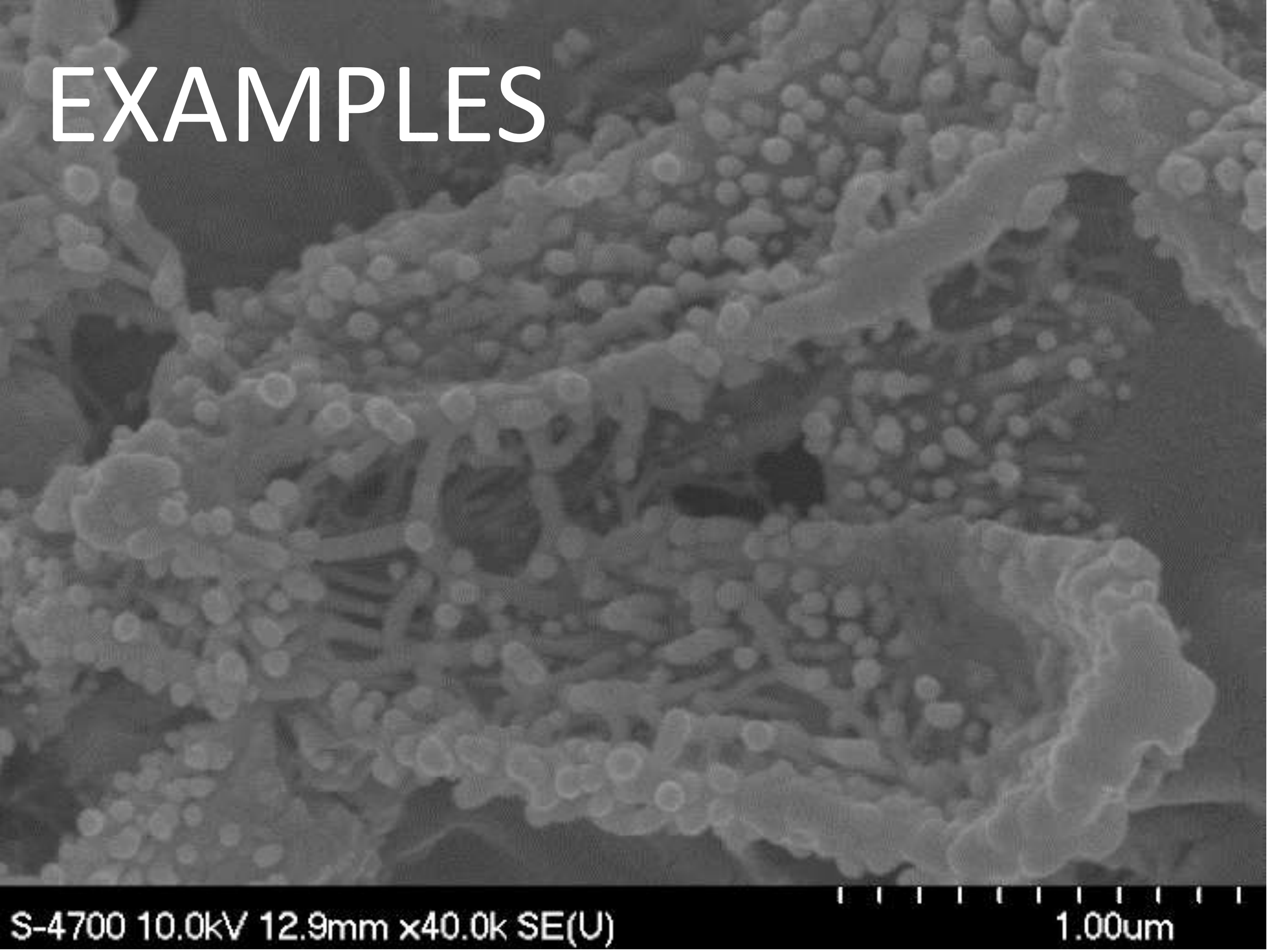


Image courtesy of Cole Edwards

NANOSPHERES PRESENT IN PRECAMBRIAN ROCKS

Here in Palaeoproterozoic chert.

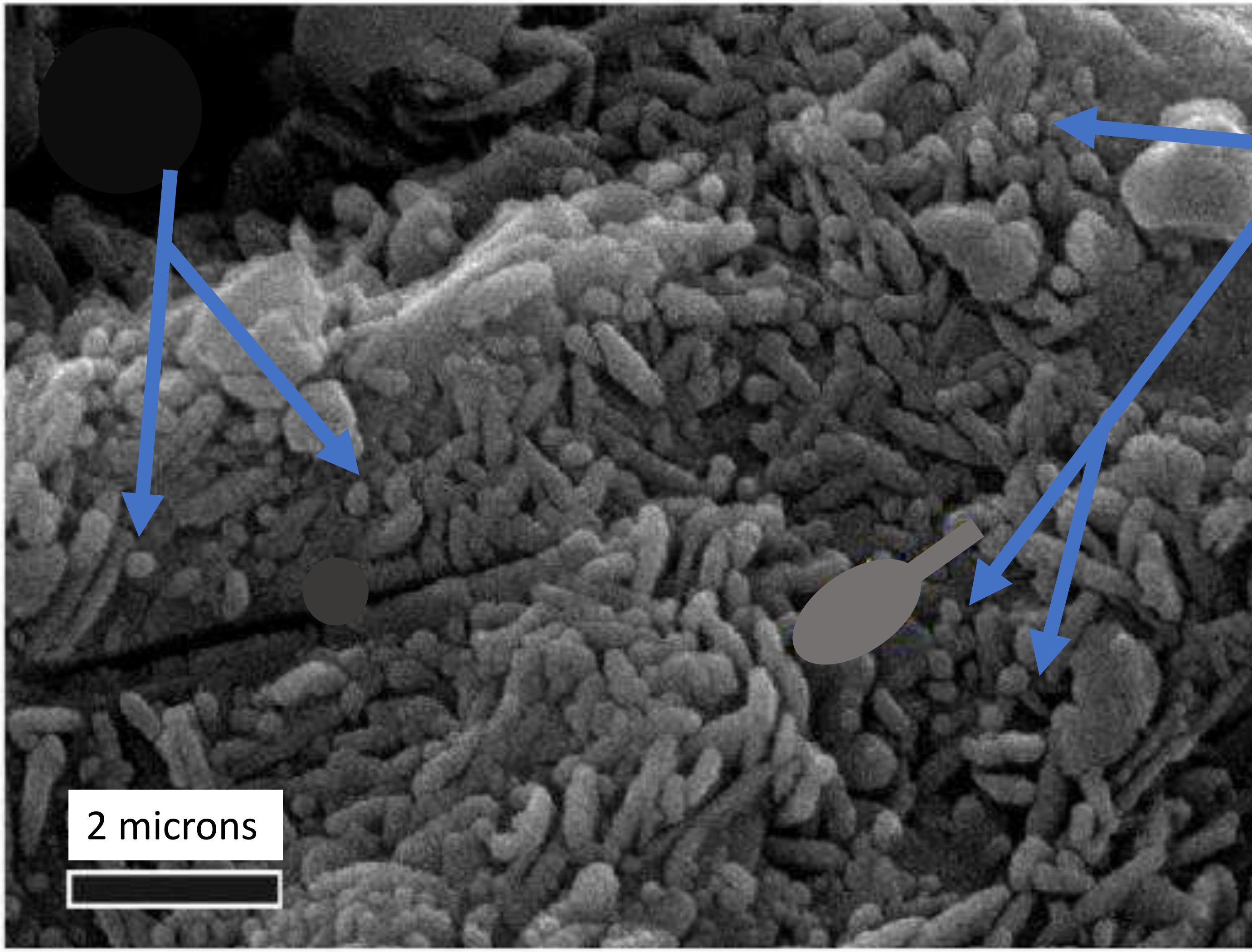
Silicified microfossils Labrador, Canada, 1.88 Ga, showing microbial filaments and numerous nanospheres.

THESE NANOSPHERES COULD BE SILICIFIED VIRUSES.

Note their size – really tiny, 50-70 nm, and shape (not perfect spheres).

Edwards et al. (2012) Precambrian Research.

AND HERE IN A PALAEOPROTEROZOIC PHOSPHORITE:



Numerous nanospheres amongst the relics of microbial filaments.

ARE THESE PHOSPHATISED VIRUSES ?

Notice their shape and similar size.

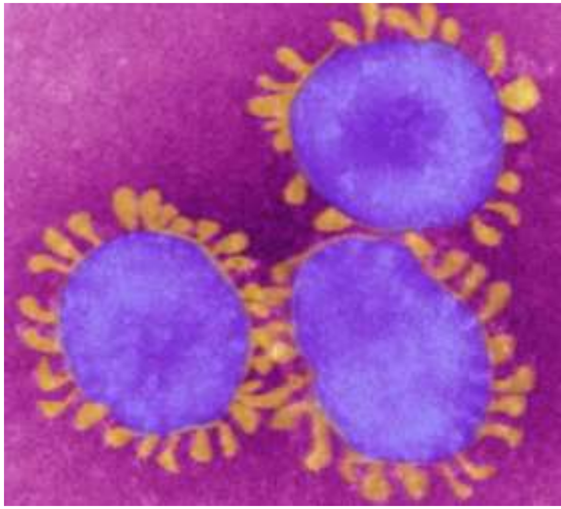
1.85 Ga Michigamme Fm, Labrador, Canada. Palaeoproterozoic tidal-flat phosphorite. Hiatt et al. (2015).

BUT: IS THERE A SIGNIFICANCE FOR VIRUSES BEYOND MICROBIAL MATS and PANDEMICS ?

VIRUSES ARE NOT ALL BAD: THEY DO MUCH GOOD IN THE WORLD

in terms of biogeochemical cycles and biological diversity

Recycling of organic matter: Through infection and cell lysis, viruses are responsible for the death of nearly 80% of all prokaryotes (i.e. bacteria and archaea), so releasing nitrogen, carbon and phosphorus, producing dissolved organic matter, which stimulates further microbial growth.



Nutrient supply: returning organic matter to the base of the food chain.

Marine viruses appear to **prevent bacterial population explosions**, allowing a broad diversity of species to coexist.

Viruses inducing evolution of their hosts, so improving the gene pool; signatures of that evolution present in the genetic code of organisms.

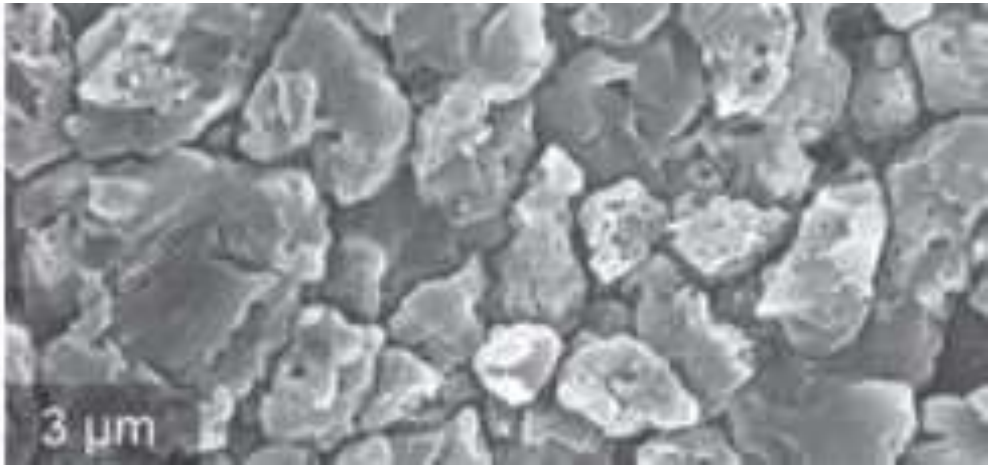
BUT WHAT ELSE – IN EARTH SCIENCES ?

FINE-GRAINED LIMESTONES COMMON THRU GEOLOGICAL RECORD:

BUT ORIGIN OF THE LIME MUD ?

SOLNHOFEN

Planktic cyanobacterial blooms and their associated viruses providing the seeds for carbonate pptn.

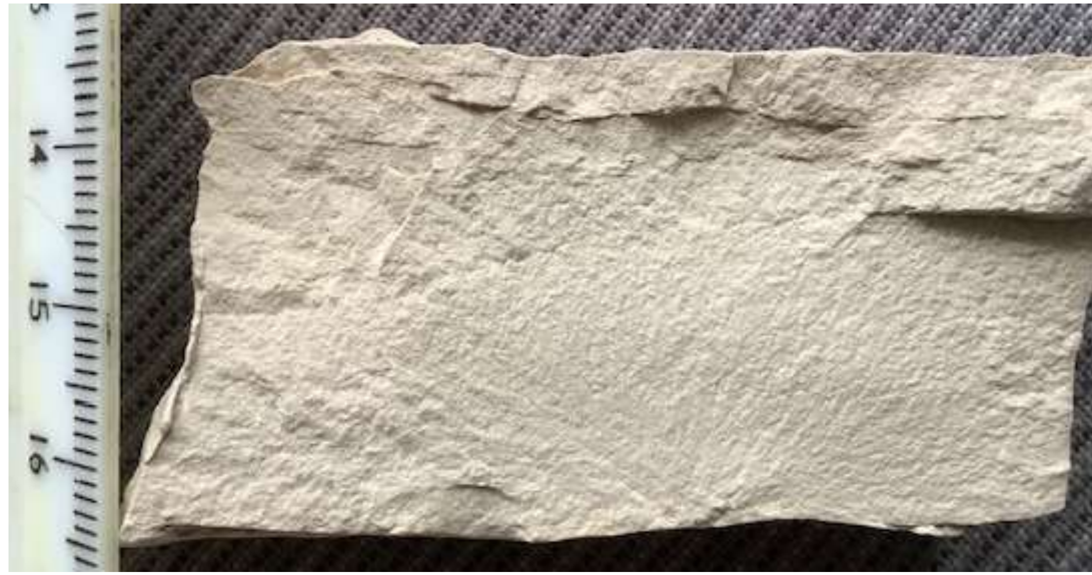


Solnhofen Limestone Upper Jurassic Bavaria.

PALAEOPROTEROZOIC, CHATTISGARH BASIN, INDIA

LIME MUD PRECIPITATED VIA PLANKTIC MICROBES AND THEIR VIRUSES

HERE IN BATH: Rhaetic, Upper Triassic.
White Lias – Saltford, Keynsham – fine grained micritic limestone



Temporary exposure Keynsham; also Saltford, and old Hartwell Garage, Upper Bristol Road, Bath. Useful building stone (and Roman tesserae).

An extremely fine limestone: but how precipitated ?
simply out of seawater – unlikely – would need a trigger.
Could that be a bloom of microbes with their viruses ?
induced by climate, dust, upwelling, river flood increasing nutrients ?

ARE THESE VIRALITES ?

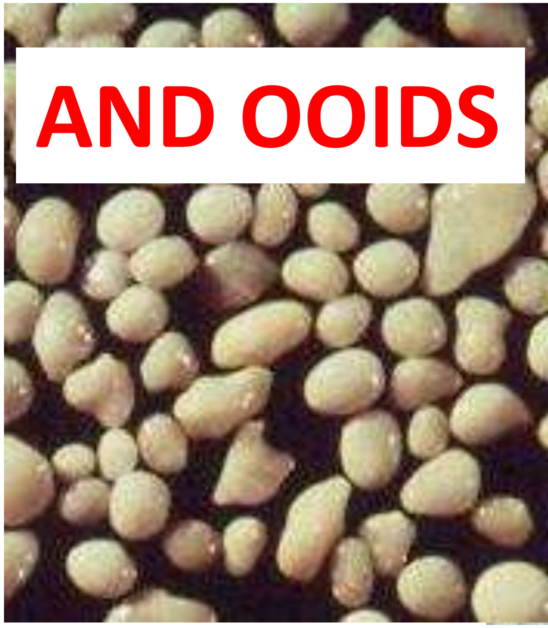
WHITINGS

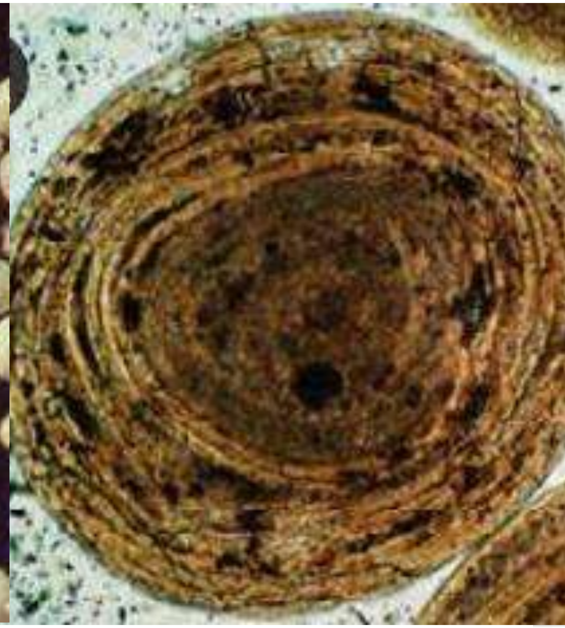
Viruses could provide the seeds for mineral precipitation as in lime mud precipitation

WHITINGS in the Bahamas: off-platform currents bringing supersaturated seawater on to GBB (Purkis et al. 2017) AND/OR effect of wind-blown Saharan dust (Swart et al. 2014), **inducing $CaCO_3$ precipitation through photosynthetic activity of planktic cyanobacteria**

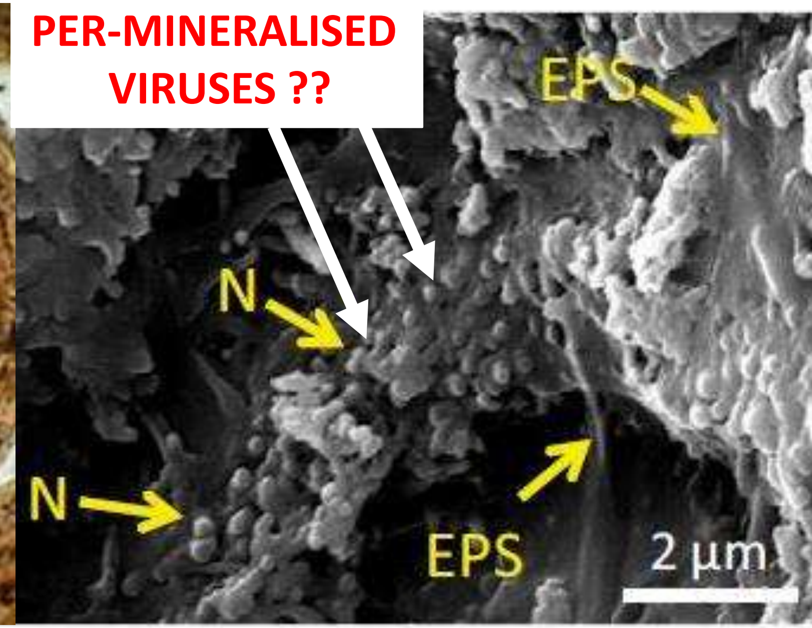
PLUS THEIR ASSOCIATED VIRUSES.

AND OOIDS

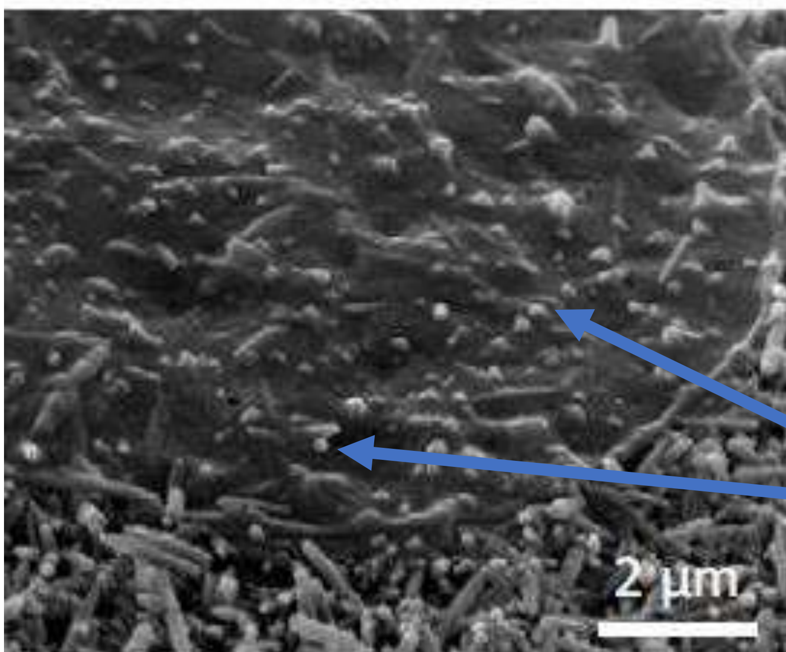




PER-MINERALISED VIRUSES ??



OOIDS NOW SUGGESTED AS MICROBIAL IN ORIGIN (Diaz et al. 2017, 2019)



because bacteria and EPS found.

BUT:

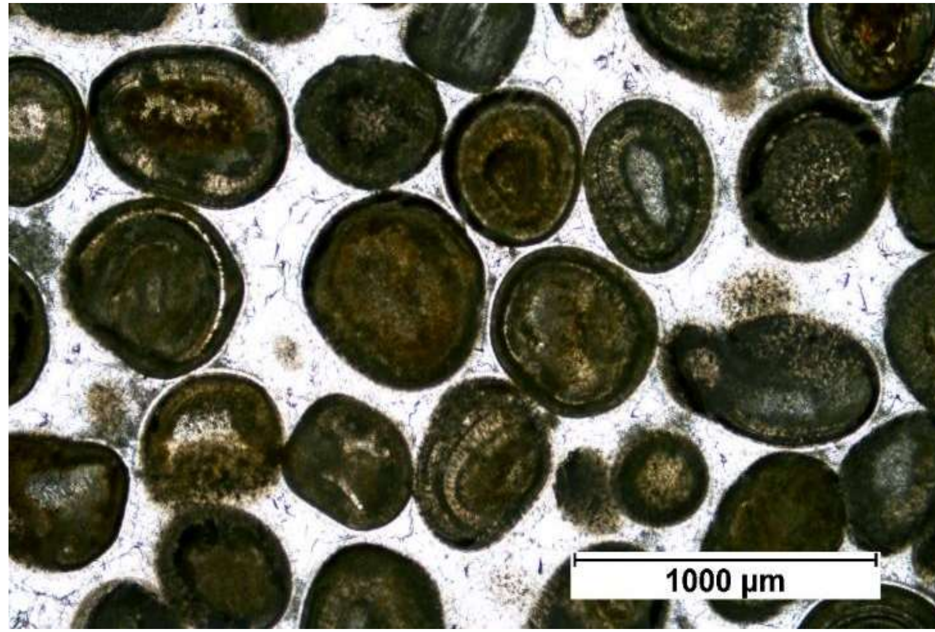
Ooids are full of nanospheres (N):

Scattered and clusters of nanograins (N) associated with mucus (EPS). Composition is ACC (amorphous calcium carbonate), converts to calcite-aragonite.

ARE THESE PER-MINERALISED VIRUSES ??

From Diaz et al. (2017, 2019) Geology, ESR.

AND MANY OOLITES IN THE JURASSIC HERE:
BATH STONE / GREAT OOLITE (& INFERIOR OOLITE)
ALSO IN THE CARBONIFEROUS – GULLY OOLITE (AVON GORGE)

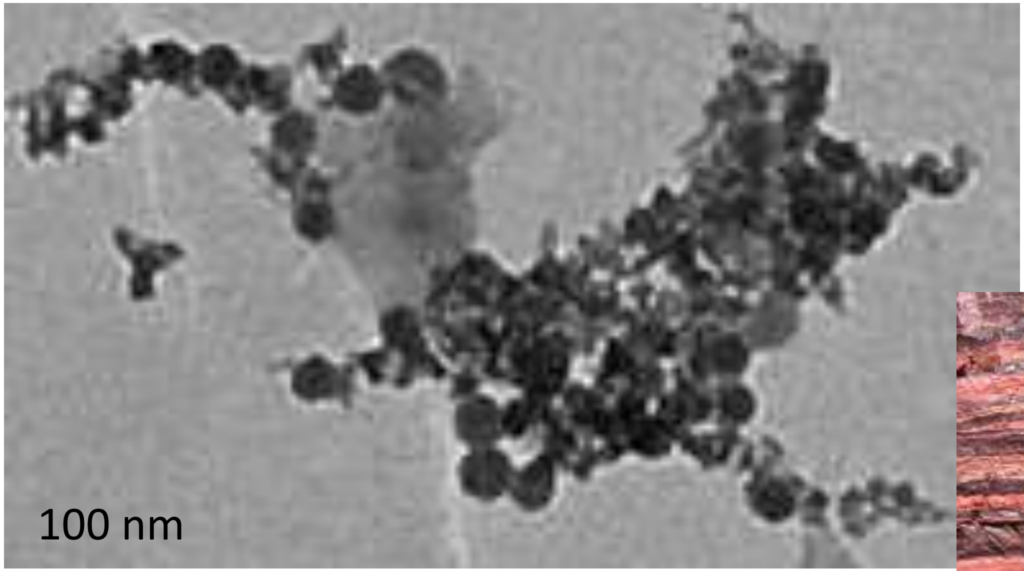


BATH OOLITE oolitic grainstone with few bioclasts (shells)

Another VIRALITE ?

Cross-bedded shelly oolitic grainstone + burrows

AND VIRUSES ASSOCIATED WITH IRON PRECIPITATION



TEM images of iron mineral particles associated with *Siphoviridae* viral capsids.

Virus mineralization at low pH in the Rio Tinto, Spain (Kyle et al. 2008).
Viral capsids with iron-bearing minerals sorbed to their surfaces.

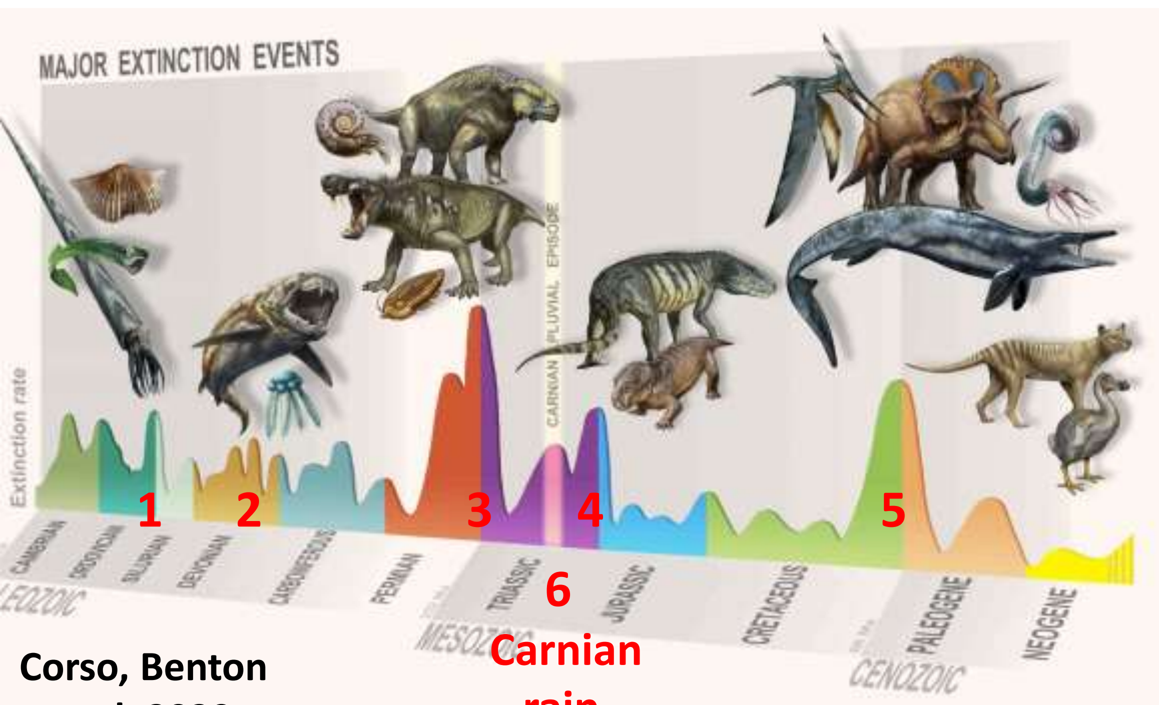
IMPLICATIONS FOR ALL IRON FORMATIONS
e.g. BIFs IN THE PRECAMBRIAN
Viruses and ore deposits

ANOTHER VIRALITE !!

AND FINALLY: WHAT ABOUT VIRUSES AND EXTINCTION ? COULD THEY PLAY A ROLE THERE ?

Two types of extinction: mass extinctions and background extinctions.

With many organisms, extinction events every few million years: coccoliths, foraminifera, ammonites etc: hence used in BIOSTRATIGRAPHY. Suggested by Emiliani (1993) background extinctions caused by a host-specific viral action, a fundamental part of the process of evolution, related to an environmental 'upset'.



Corso, Benton et al. 2020

Mass extinctions: catastrophic events: meteorite, volcanism, climate, sixth just recognised.
BUT
Background extinctions more subtle, more species-specific, environment-driven, ? toxins, viruses very likely involved.

THE FIELD IS OPEN – FOR FURTHER RESEARCH

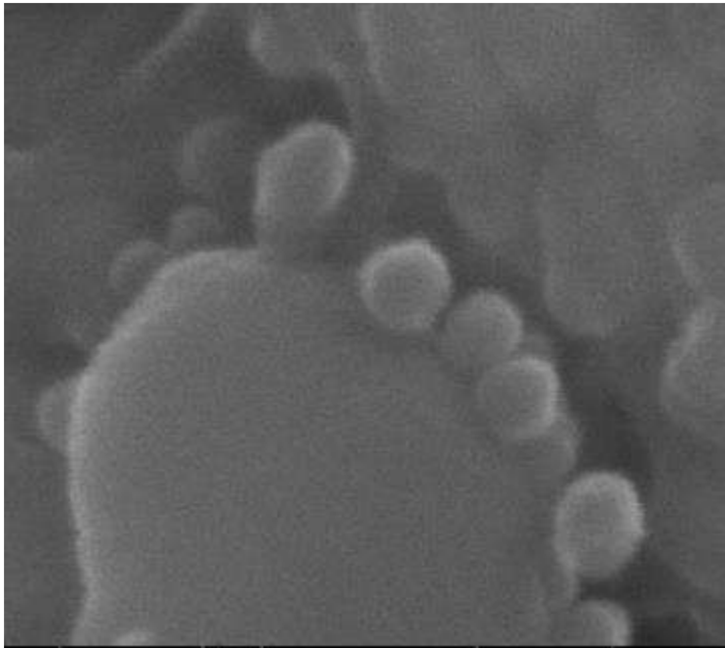
CONCLUSIONS

Viruses are completely neglected in Earth Sciences –
they must have played many roles…

Viruses do become fossilised and can be found back to
Precambrian rocks

Viruses can be the seeds for carbonate (and other mineral)
precipitation – viruses can form rocks

The role of viruses in species extinction
needs to be explored



VIRUSES are the new frontier in Earth Sciences …

And this is why I am a sedimentologist !!

Fieldwork, Los Roques, Venezuela

THANK YOU

FOR FURTHER INFORMATION SEE:

Tucker, M.E. (2020) Fossil viruses. Geology Today, 36, 56-60.

Slowakiewicz et al. (2021) Expts with viruses. GCA 292.

An icosahedral dice –
from Ptolemaic Egypt,
a Hellenistic dynasty
founded 305 BC, until 30 BC
when Cleopatra took over.

Background vs Mass Extinction

- **Mass Extinctions: Only 4%**
  - Mass Extinctions kill off a very large % of the species on the planet at a given time, but because they are short in duration, they comprise a small % of animals that ever lived on the planet
- **Background Extinctions: 96%**
  - Extinctions are always happening in the background, and over a long long period of time, these extinctions add up to a lot of species extinctions

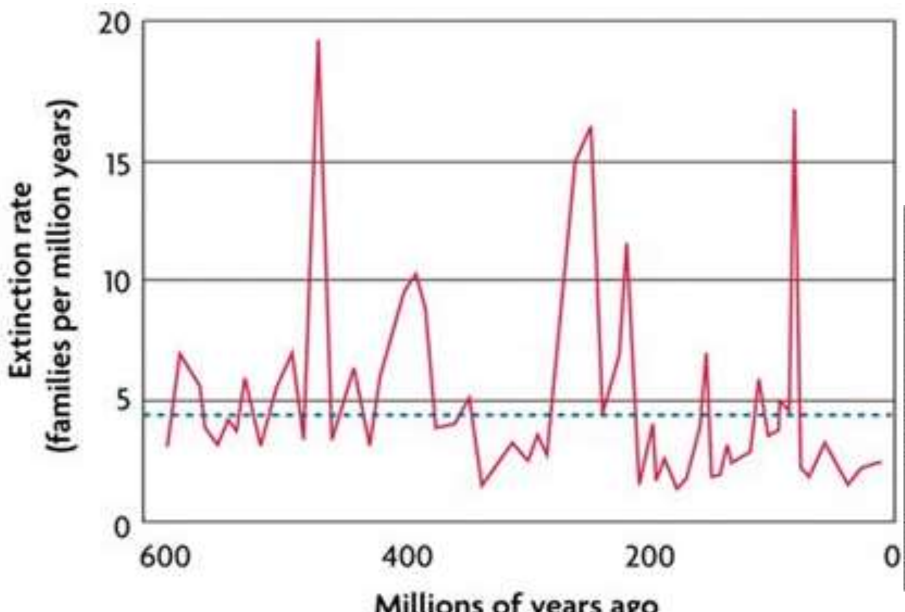
Background Extinctions:

- **Cause:** Local changes in environment
  - Forest fires, habitat destruction.
- Affects a few species in a small area
  - Less severe.
- Occur at roughly the same rate as speciation

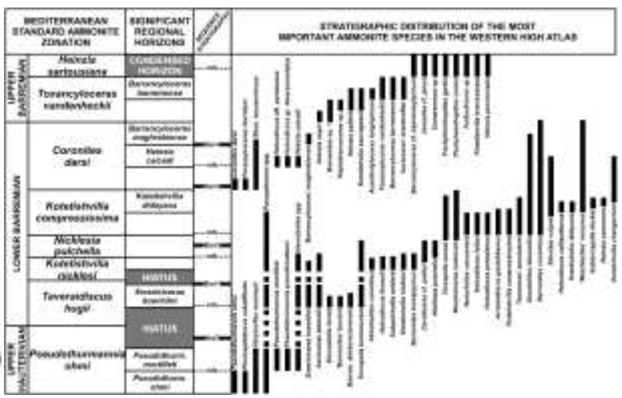
Mass Extinctions:

- **Cause:** Catastrophic events
  - Ice Age, Meteorites
- Destroys many species at global level
  - Very severe
- Rare but much more intense
  - At least 5 mass extinctions in last 600 million years

- **99% of species that have lived are extinct**

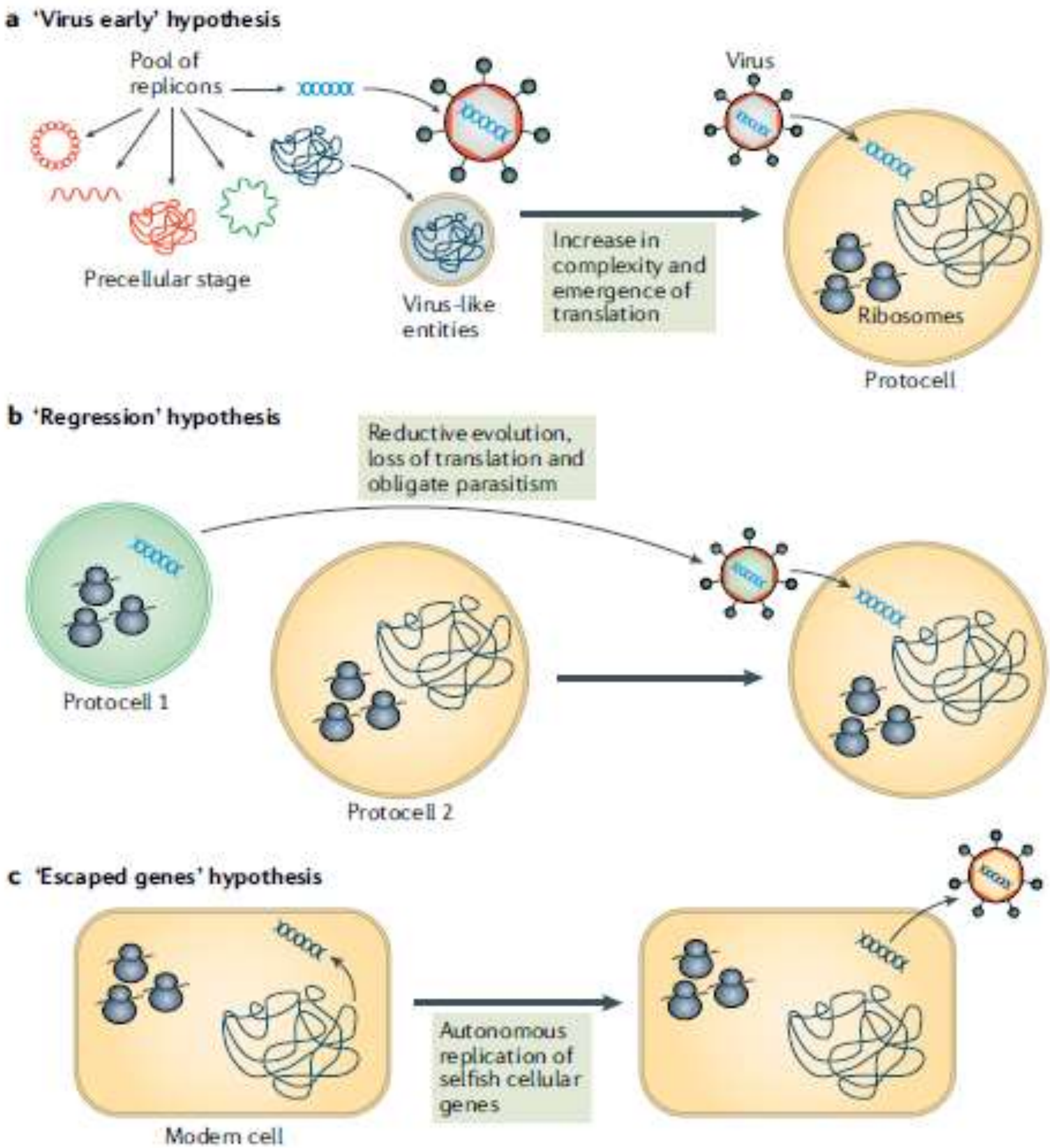


When extinction rate is plotted against time, mass extinctions appear as periodic peaks rising above background extinction levels.



Jurassic ammonites, Morocco

EXTINCTIONS – AN EVERYDAY STORY IN EARTH HISTORY



The three major scenarios for the origin of viruses.

A: The 'virus early' hypothesis assumes that viruses evolved from early replicative elements that preceded the first cellular life forms.

B: The 'regression' hypothesis suggests that viruses emerged through the degeneration of cells that then assumed a parasitic lifestyle.

C: Finally, the 'escaped genes' hypothesis proposes that cellular genes acquired the ability for 'selfish' replication and spread.