Since 1959

Common minerals disintegrate in microdroplets forming nanoparticles

(A path to sustainable agriculture)

Matter in confinement for sustainability

Thalappil Pradeep
Institute Professor, IIT Madras
https://pradeepresearch.org/
pradeep@iitm.ac.in

Co-founder

InnoNano Research Pvt. Ltd.
InnoDI Water Technologies Pvt. Ltd.
VayuJAL Technologies Pvt. Ltd.
Aqueasy Innovations Pvt. Ltd.
Hydromaterials Pvt. Ltd.
EyeNetAqua Pvt. Ltd.
Deepspectrum Analytics Pvt. Ltd.

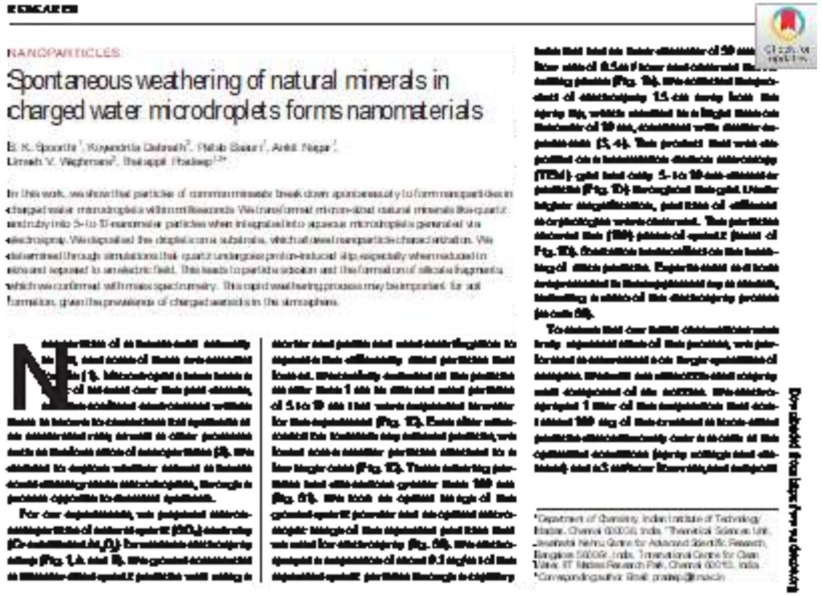
Professor-in-charge

International Centre for Clean Water

IUPAC 2025, 50th World Chemistry Congress July 14-19, 2025

Congratulations, Graham!

Science



RESEARCH

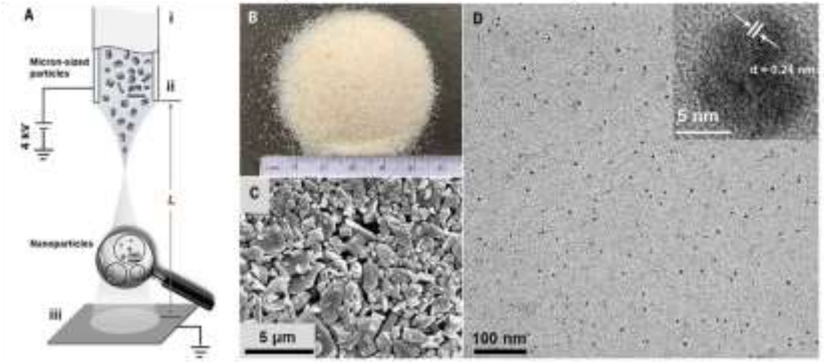
NANOPARTICLES

Spontaneous weathering of natural minerals in charged water microdroplets forms nanomaterials

B. K. Spoorthi[1], Koyendrila Debnath[2], Pallab Basuri[1], Ankit Nagar[1],
Umesh V. Waghmare[2], Thalappil Pradeep[1,3]*

In this work, we show that particles of common minerals break down spontaneously to form nanoparticles in charged water microdroplets within milliseconds. We transformed micron-sized natural minerals like quartz and ruby into 5- to 10-nanometer particles when integrated into aqueous microdroplets generated via electrospray. We deposited the droplets on a substrate, which allowed nanoparticle characterization. We determined through simulations that quartz undergoes proton-induced slip, especially when reduced in size and exposed to an electric field. This leads to particle scission and the formation of silicate fragments, which we confirmed with mass spectrometry. This rapid weathering process may be important for soil formation, given the prevalence of charged aerosols in the atmosphere.

[1] Department of Chemistry, Indian Institute of Technology Madras, Chennai 600036, India. [2] Theoretical Sciences Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560064, India. [3] International Centre for Clean Water, IIT Madras Research Park, Chennai 600113, India.
*Corresponding author. Email: pradeep@iitm.ac.in



Spoorthi et al., Science 384, 1012–1017 (2024) 31 May 2024

A scale of 1000

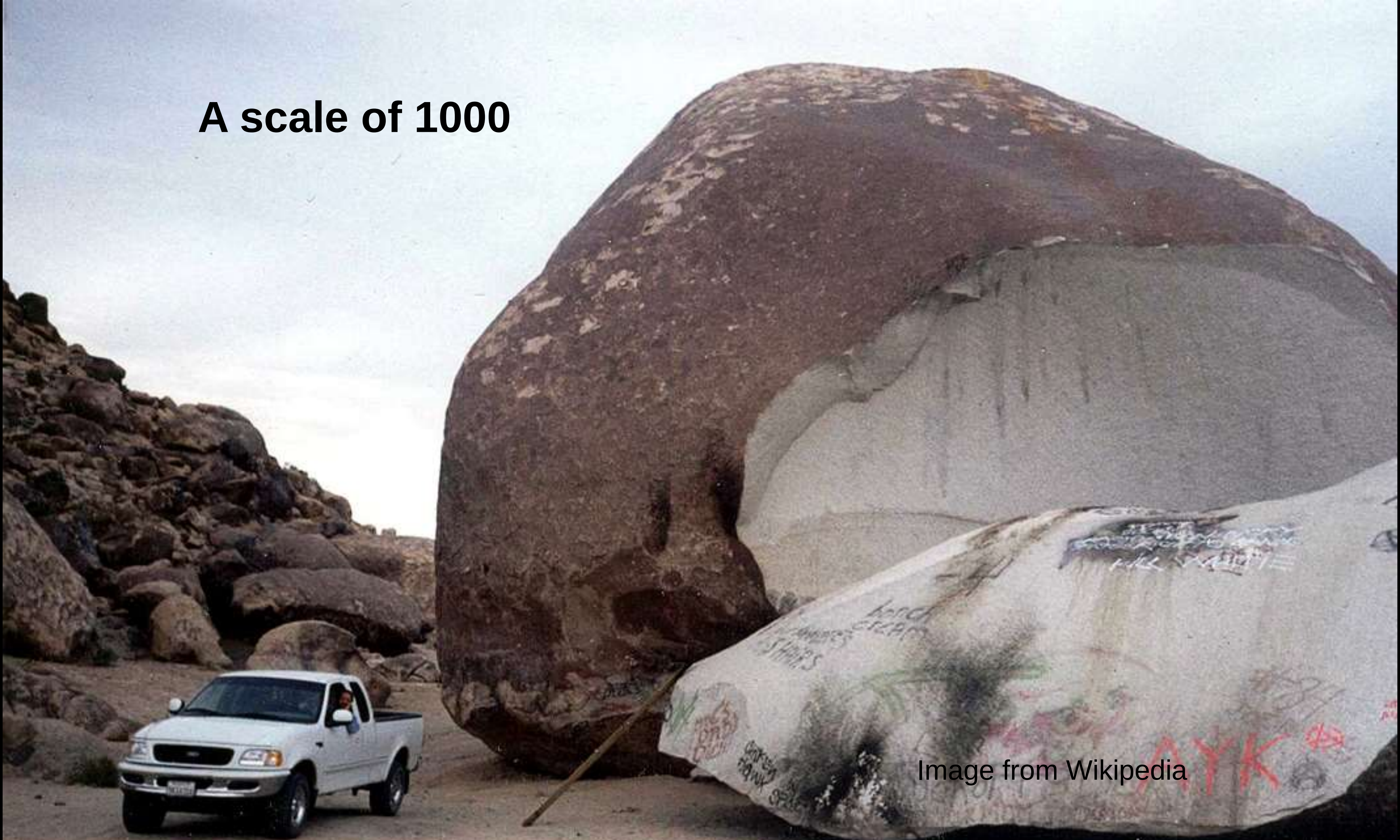
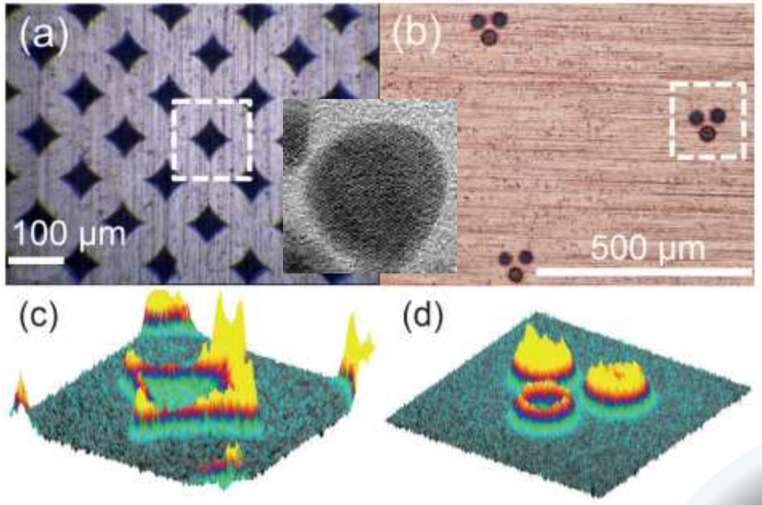
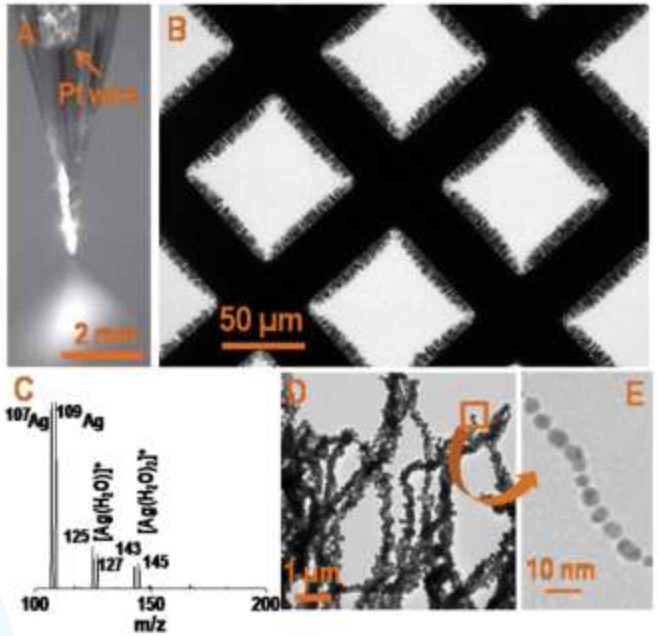


Image from Wikipedia

Functional Nanomaterials



Anyin Li, et. al., Angew. Chem. Int. Ed. 2014, 53, 12528 –12531.



Depanjan Sarkar et. al., *Adv. Mater.* 2016, 28, 2223–2228.

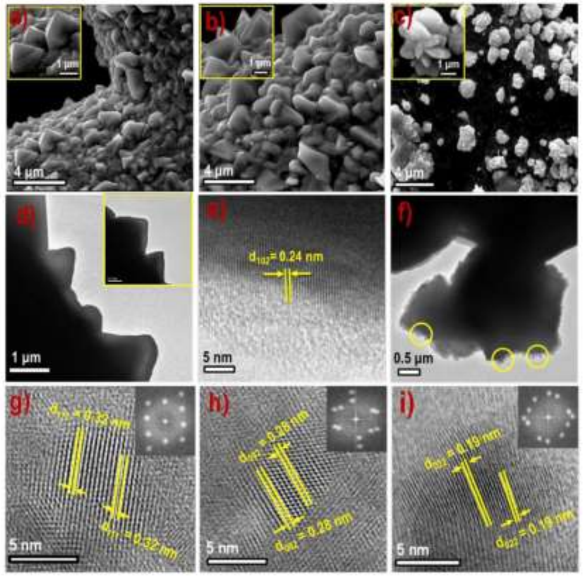
0D

1D

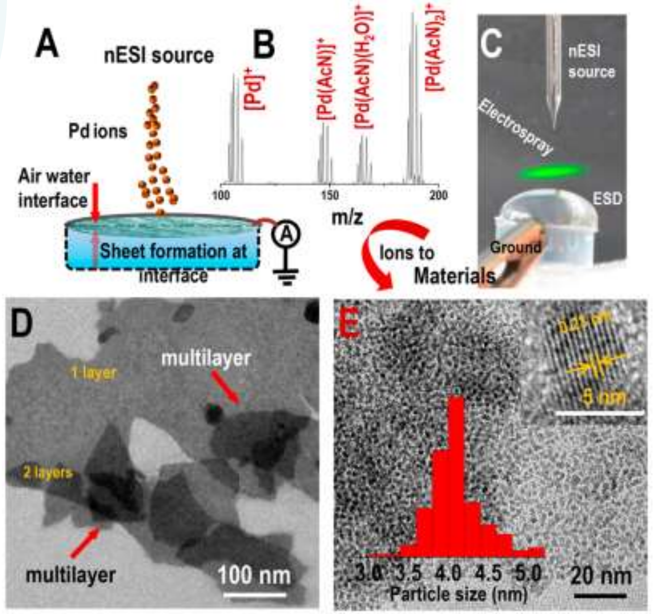
Microdroplets

3D

2D



Arijit Jana et. al., *J. Mater. Chem. A,* 2019, 7, 6387–6394.



Depanjan Sarkar, et. al., *J. Phys. Chem. C* 2018, 122, 17777−17783.

Volume 13
Number 45
7 December 2022
Pages 13251–13634

Chemical Science

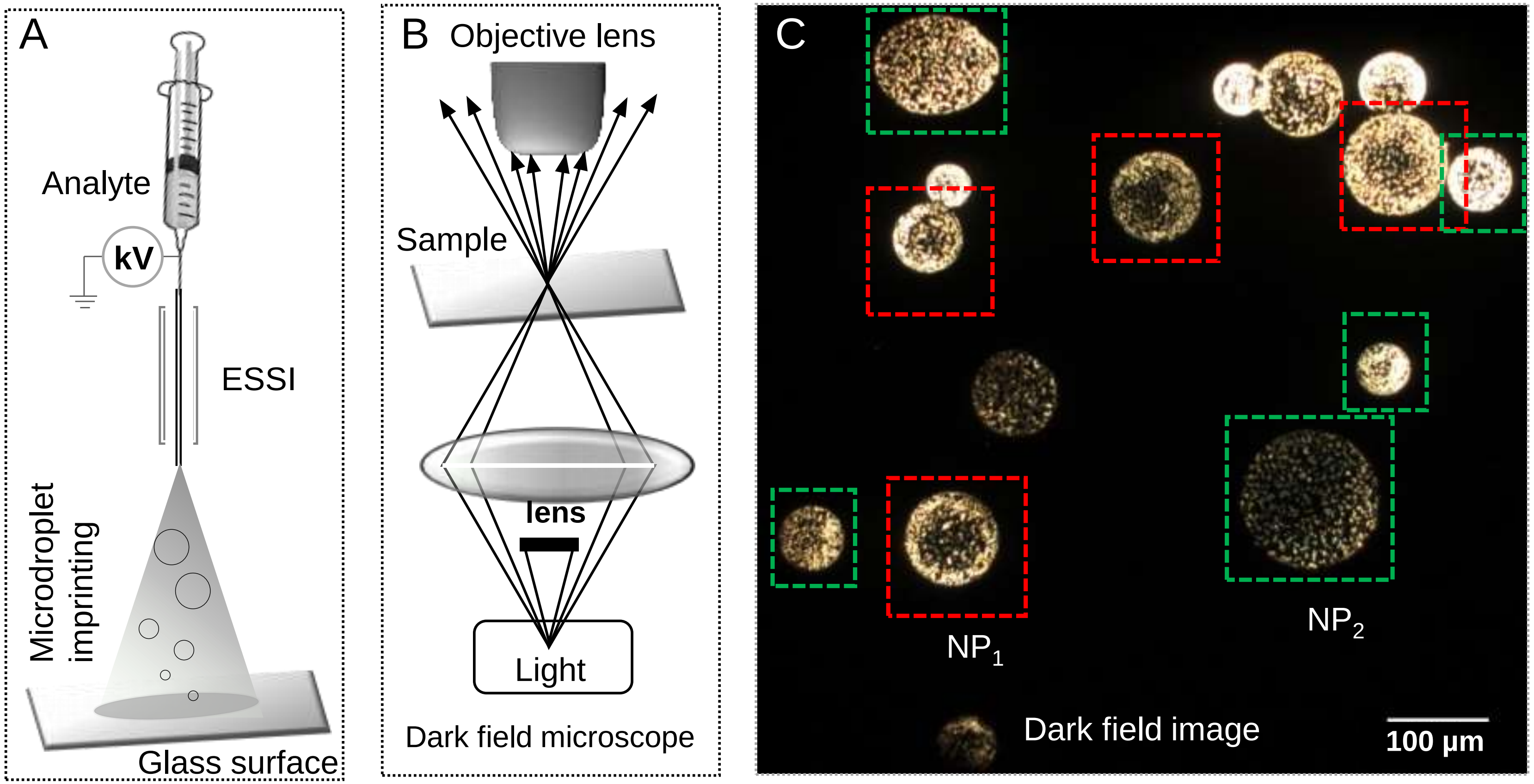
rsc.li/chemical-science

ISSN 2041-6539

ROYAL SOCIETY
OF **CHEMISTRY**

EDGE ARTICLE
Thalappil Pradeep *et al.*
Spatial reorganization of analytes in charged aqueous microdroplets

Understanding Microdroplets

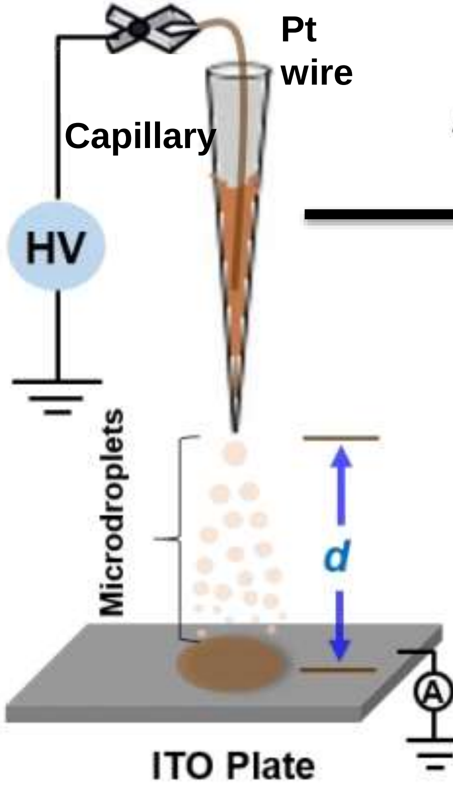


Pallab Basuri et. al. *Chem. Sci.,* 2022, 13, 13321–13329.

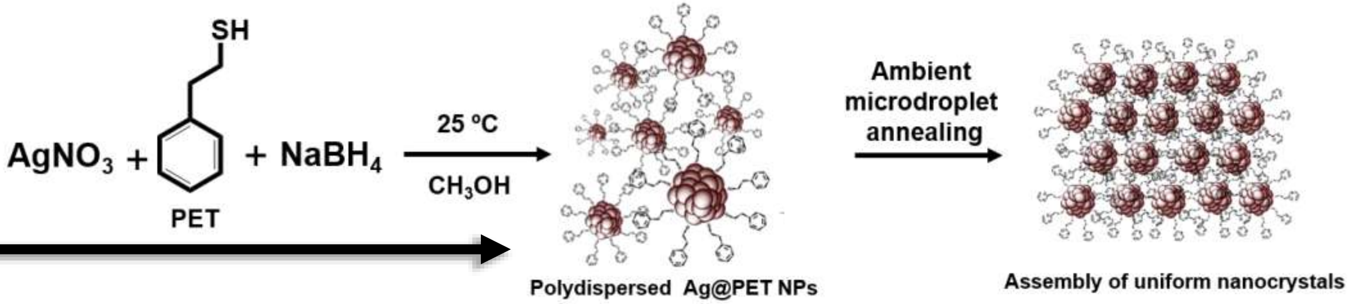
Transformation of Materials in Microdroplets

Ambient Microdroplet Annealing of Nanoparticles

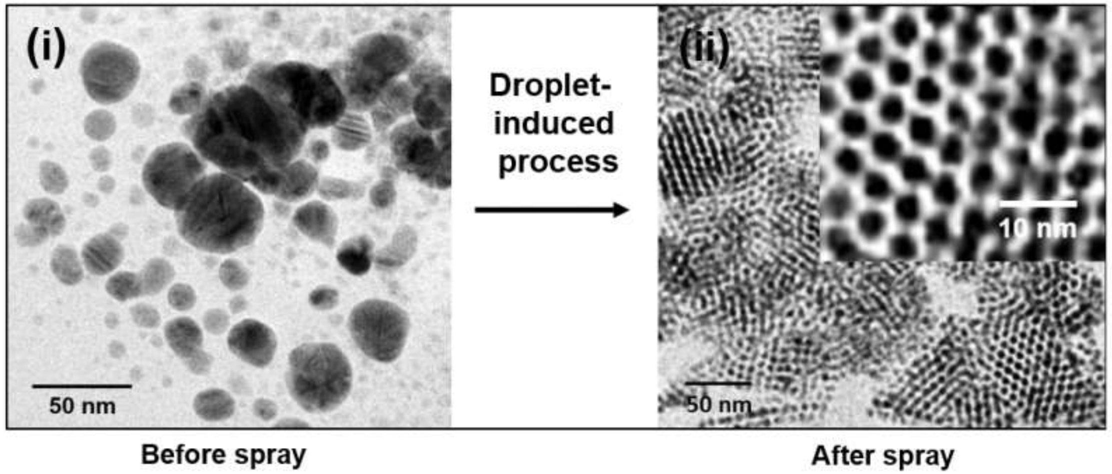
Experimental set-up



Synthesis of polydisperse NPs



Transformation process



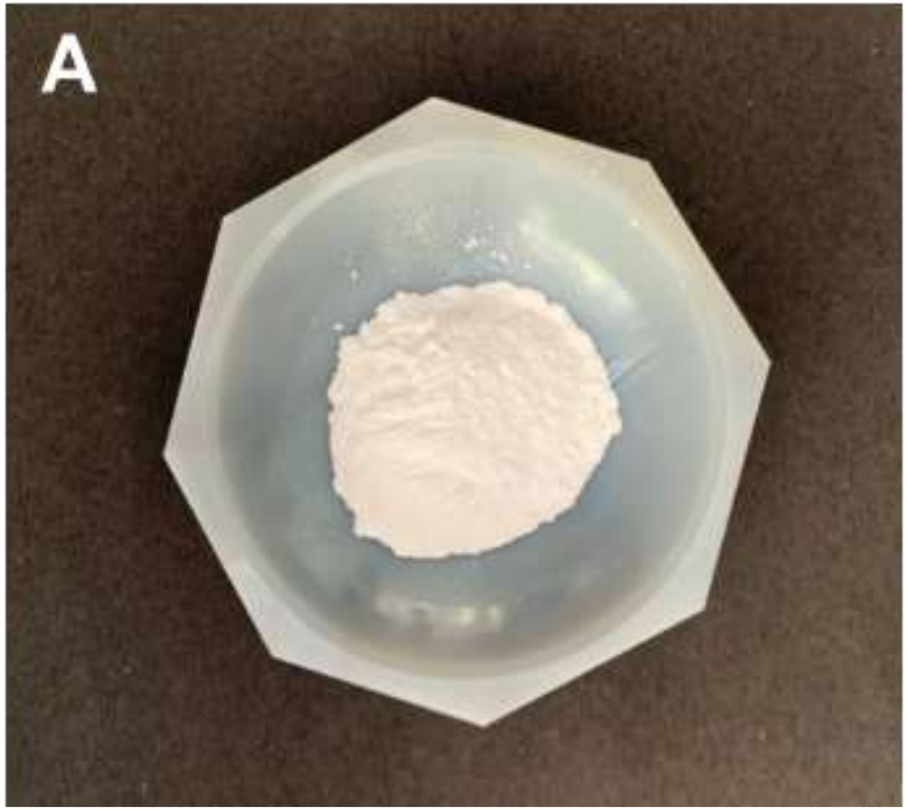
Angshuman Ray Chowdhuri et. al., *Chem. Sci.*, 2021, 12, 6370–6377.

Thanks to ChatGPT

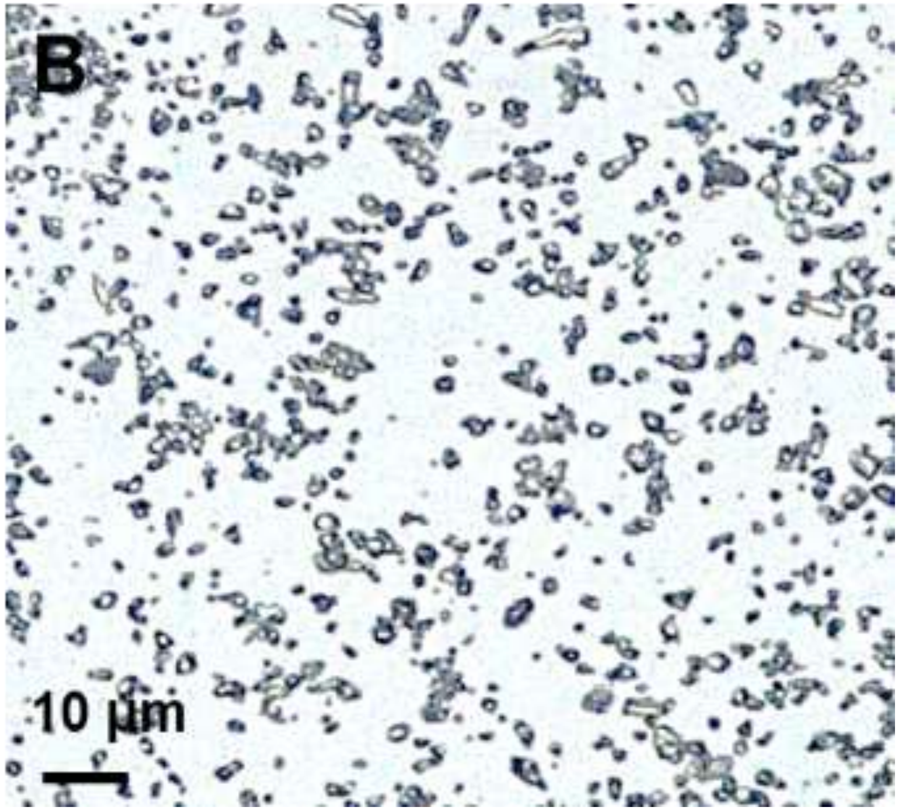
Weathering in Nature

Sand, the Ubiquitous Material

Images from Wikipedia

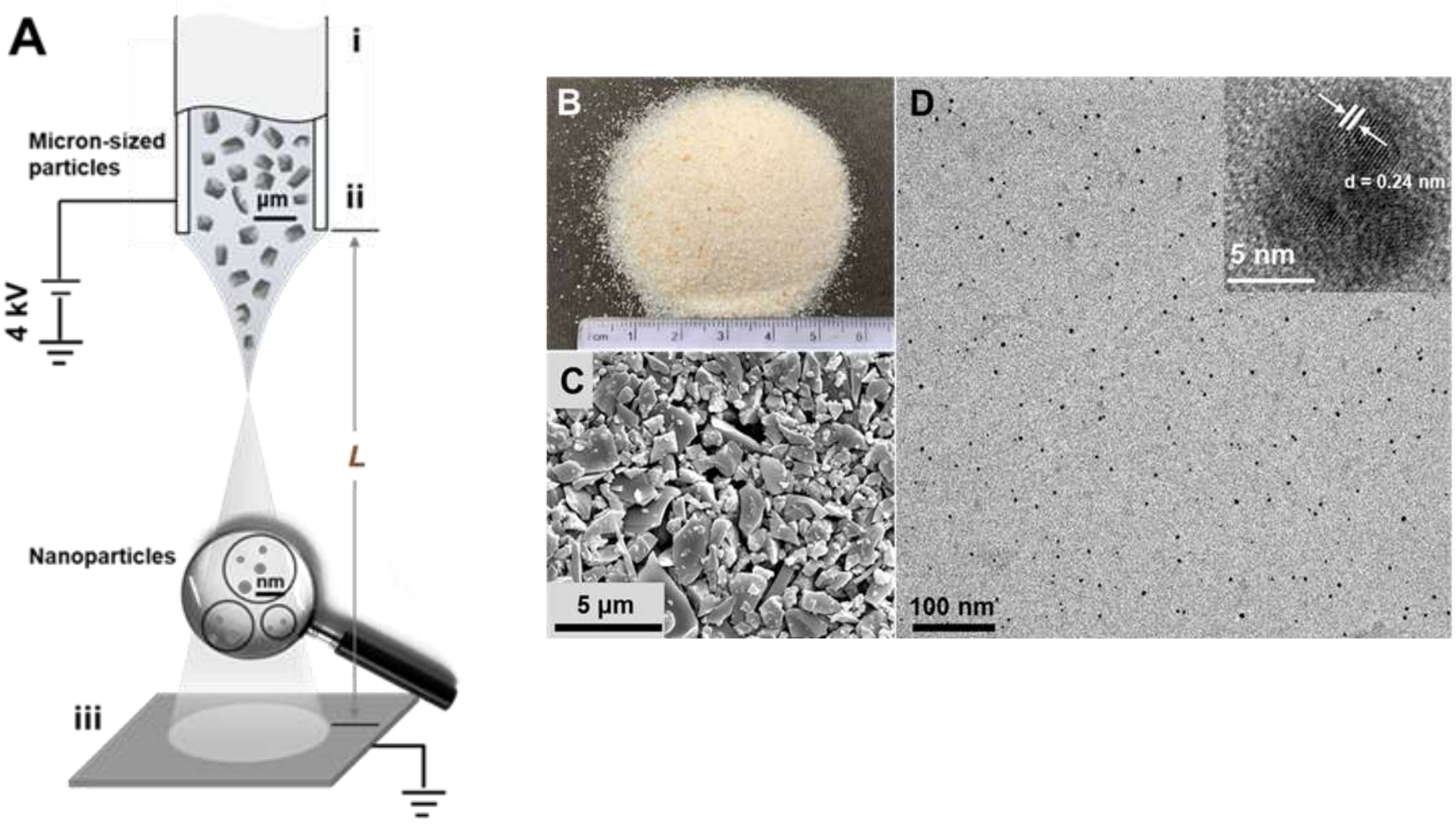


Ground silica



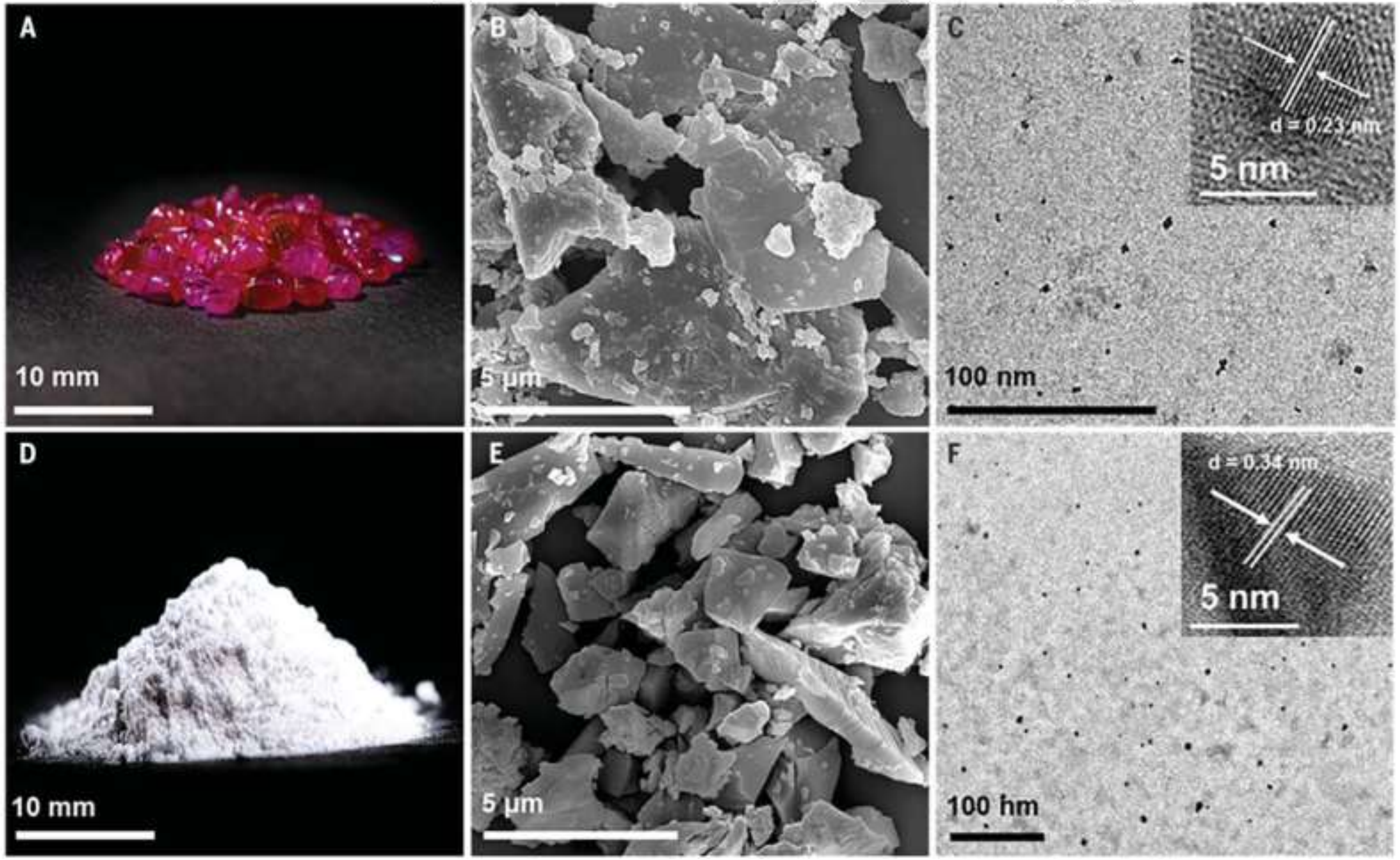
Optical image of silica

Weathering of Minerals in Microdroplets

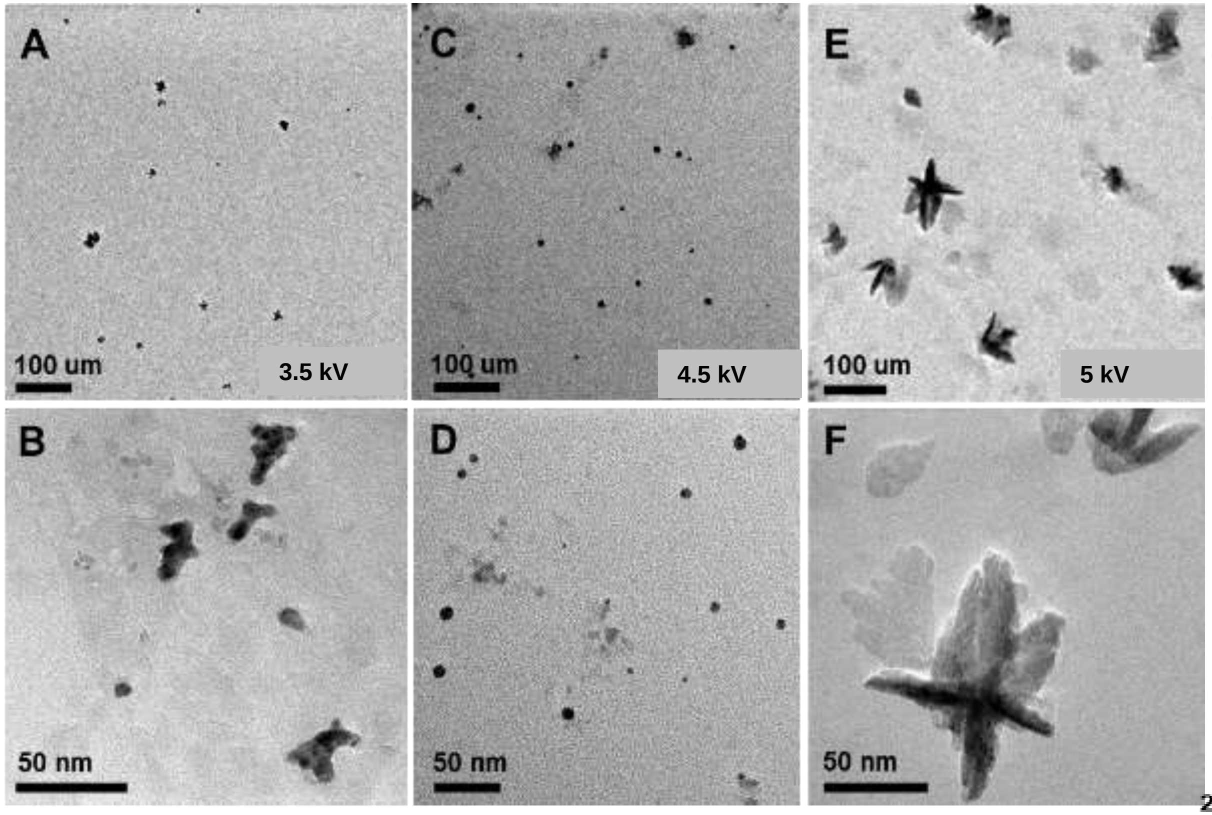


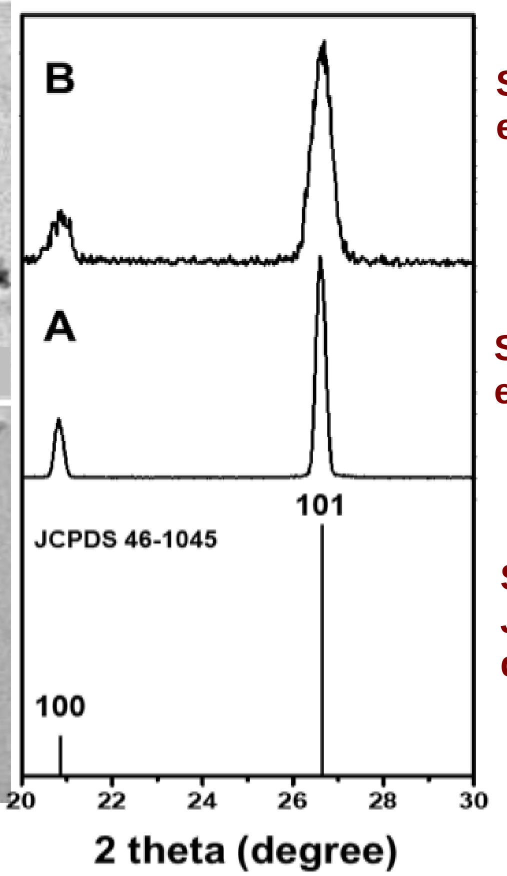
Spoorthi, et. al., *Science*, 2024

Ruby, Fused Alumina



Fragmentation of Silica – Varying Conditions





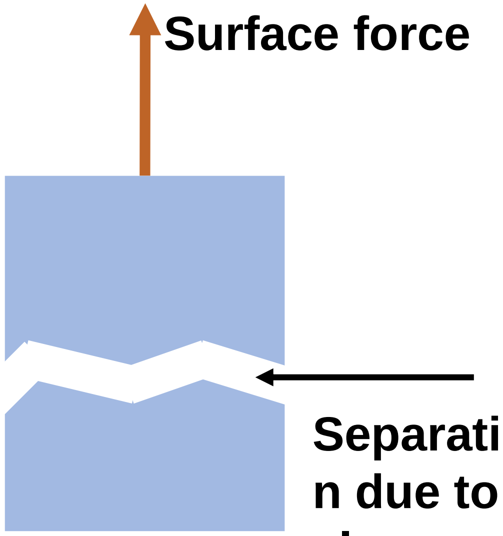
SiO_2 after electrospray

SiO_2 before electrospray

SiO_2 JCPDS data

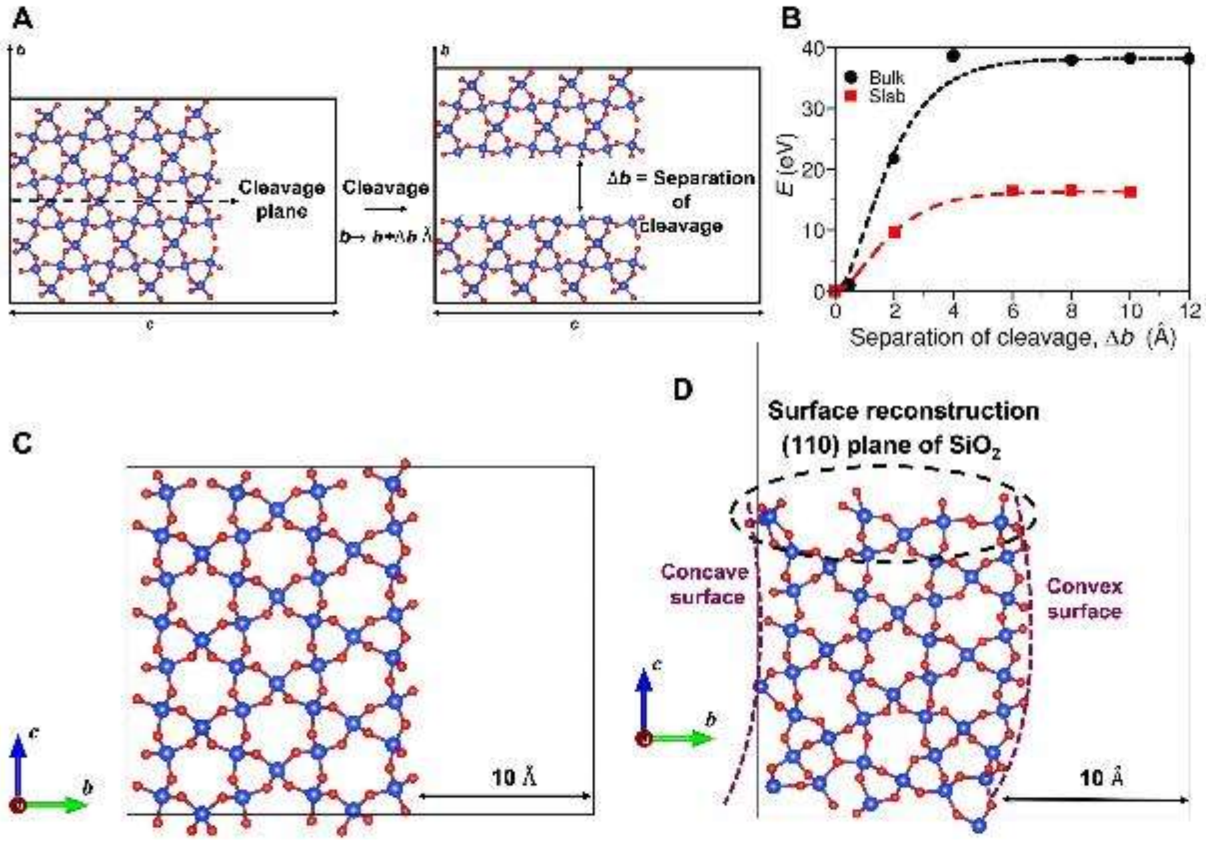
Mechanism: Cleavage

The process of cleavage and surface reconstruction visualized with first-principles simulations

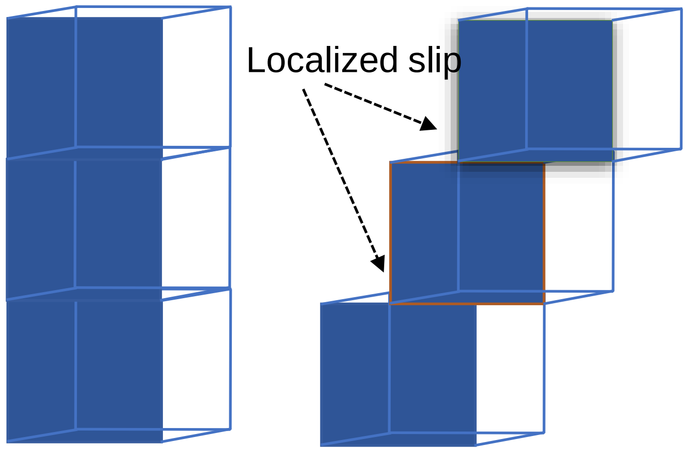


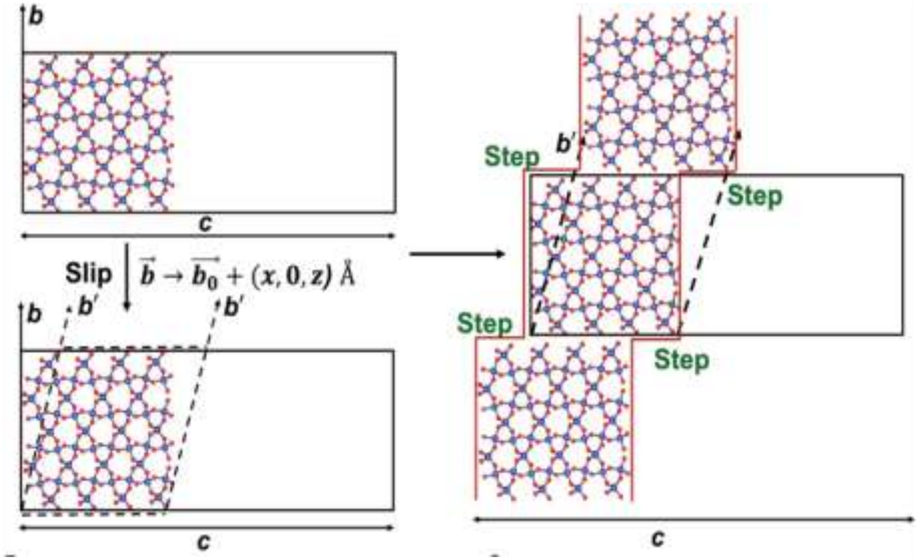
Surface force

Separation due to cleavage



Mechanism: Slip





This instability leads to the formation of a stacking fault on the (010) plane, achieved with slip localized at (010) plane

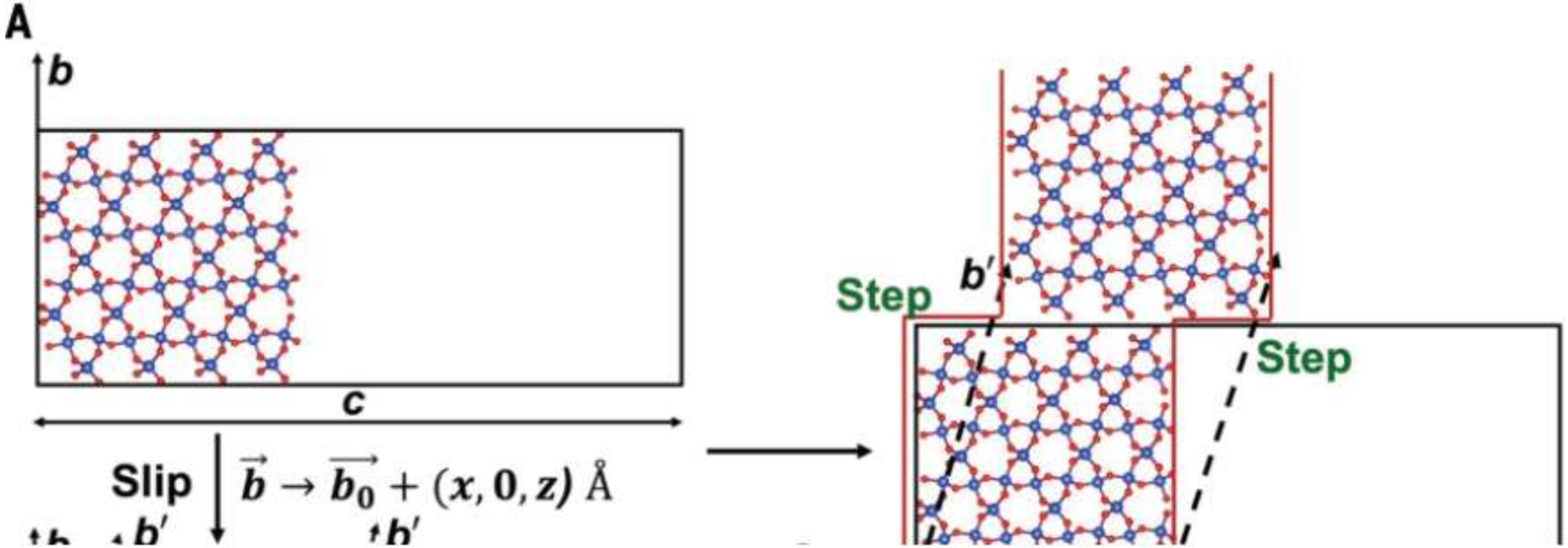
Stacking fault

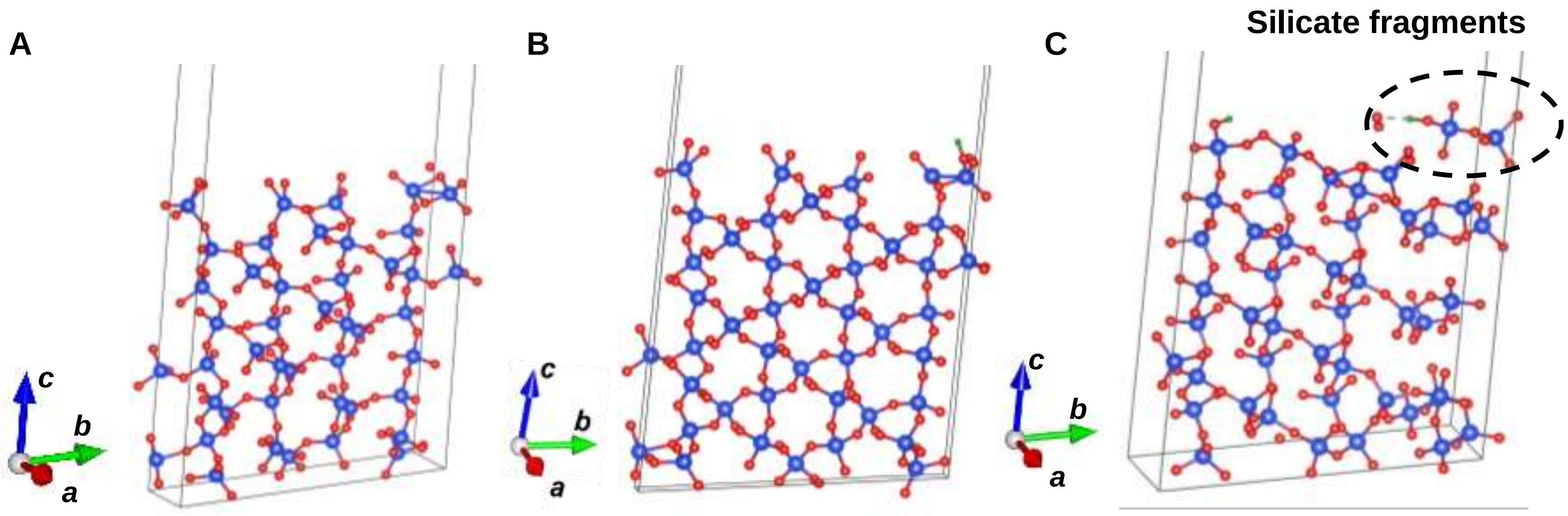
$\vec{b} \rightarrow \overrightarrow{b_0} + (x, 0, z)$,

(x, $z \in$ [0,1]) - fractional coordinates

SFEs of (010) direction with (0, 0), (0, 0.5), (0.5, 0) and (0.5, 0.5) slip configurations on the (110) plane of SiO_2

SFE (J/m^2)	Slab					
	x	z	w/o H-atom	1 H-atom	2 H-atoms	E
	0.0	0.0	0	0	0	0
	0.5	**0.5**	**-1.21**	**-0.93**	**-0.88**	**-1.20**
	0.5	0.0	1.20	1.18	0.90	1.12
	0.0	**0.5**	**-0.07**	**0.89**	**-0.83**	**-0.09**



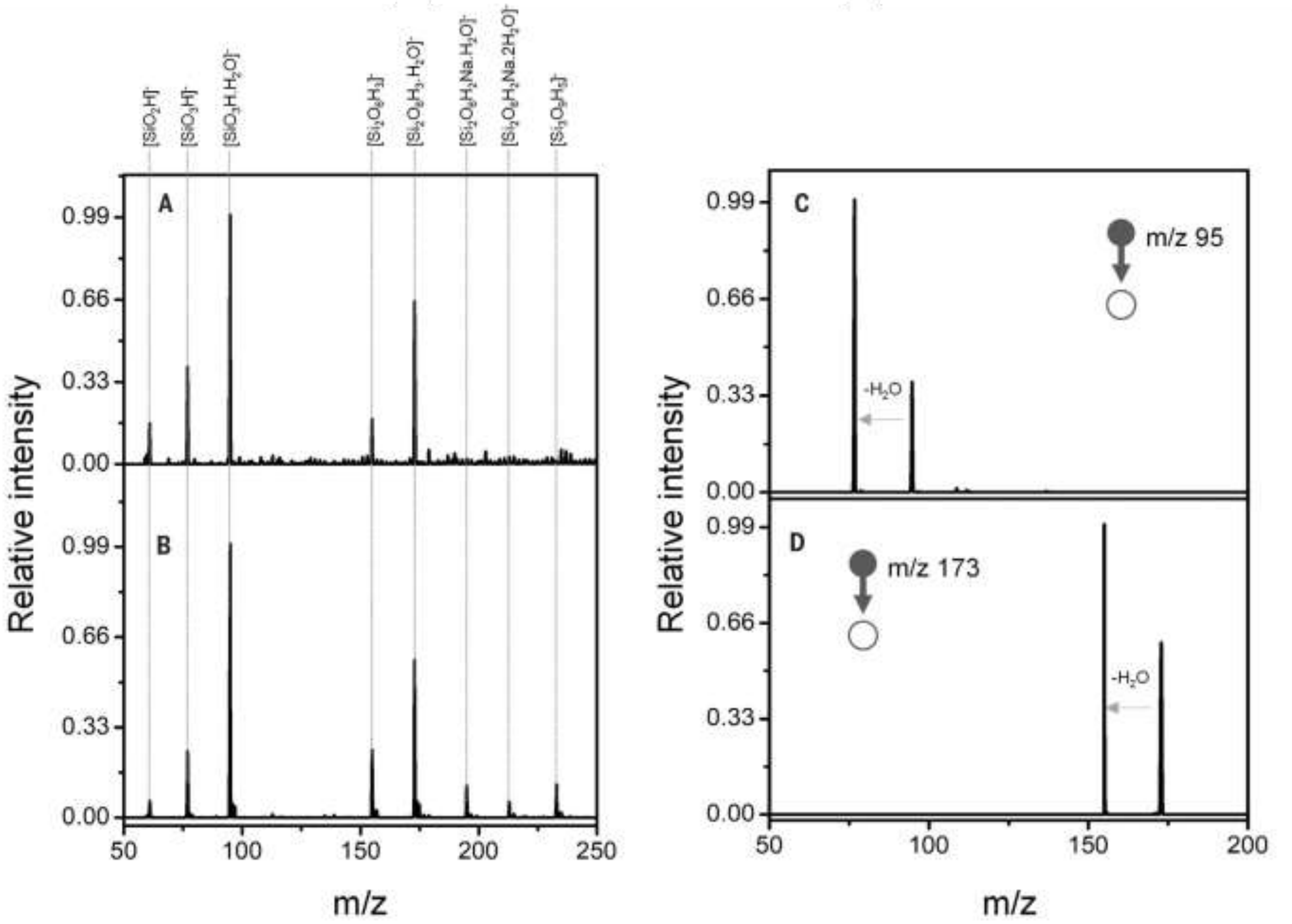


No H-atom

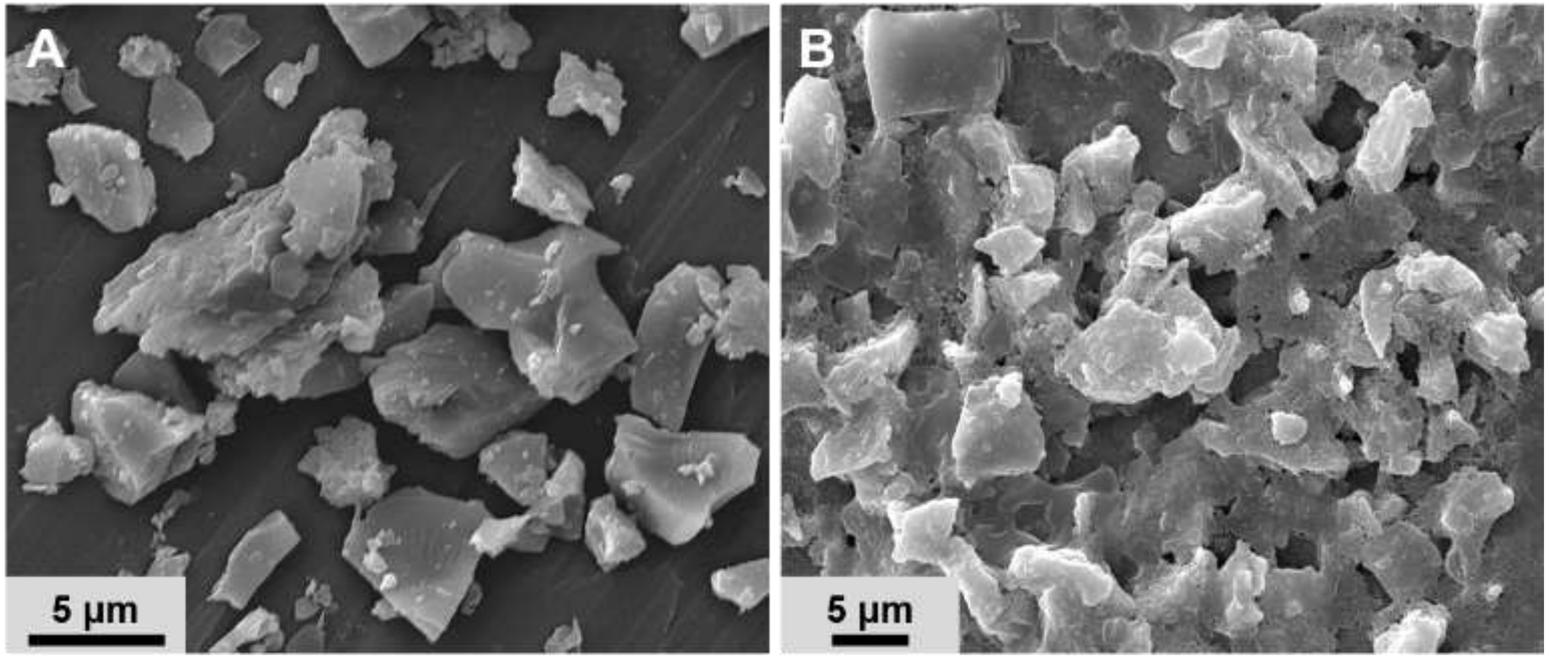
One H-atom

Two H-atoms

Mass Spectrometry of the Fragments

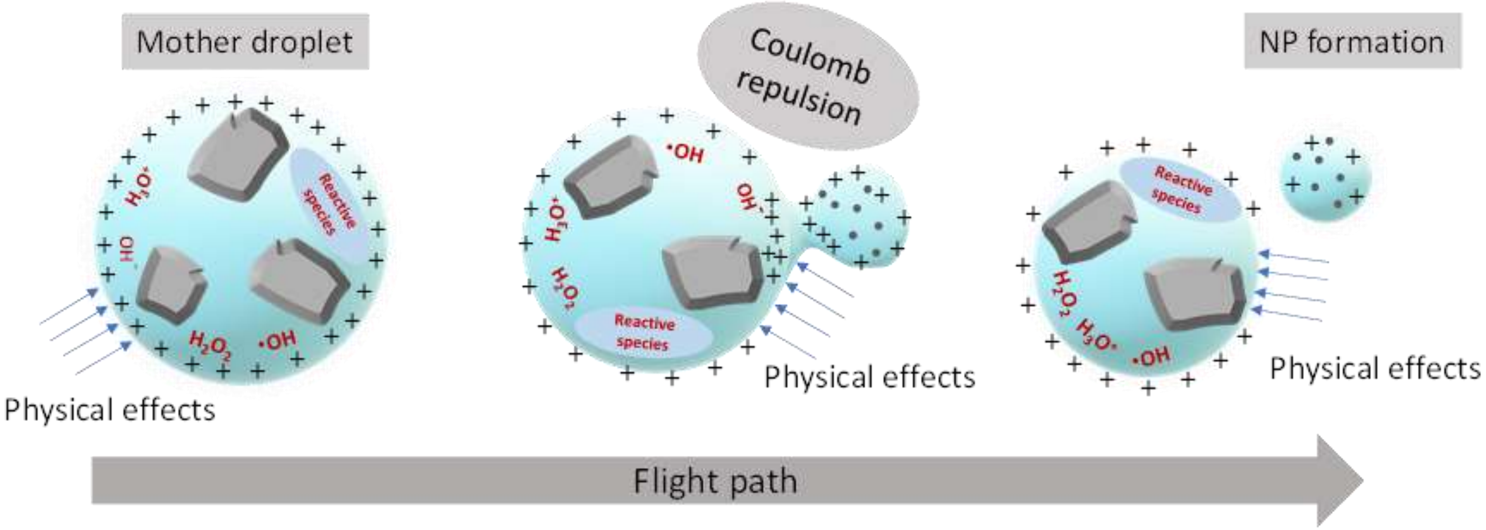


Effect of charged microdroplets on quartz



Increased surface roughness after the spray

Mechanism of nanoparticle formation



Rayleigh, On the equilibrium of liquid conducting masses charged with electricity, Philosophical Magazine, 1882

$Q = 8\pi (\epsilon_0 \gamma R^3)^{1/2}$

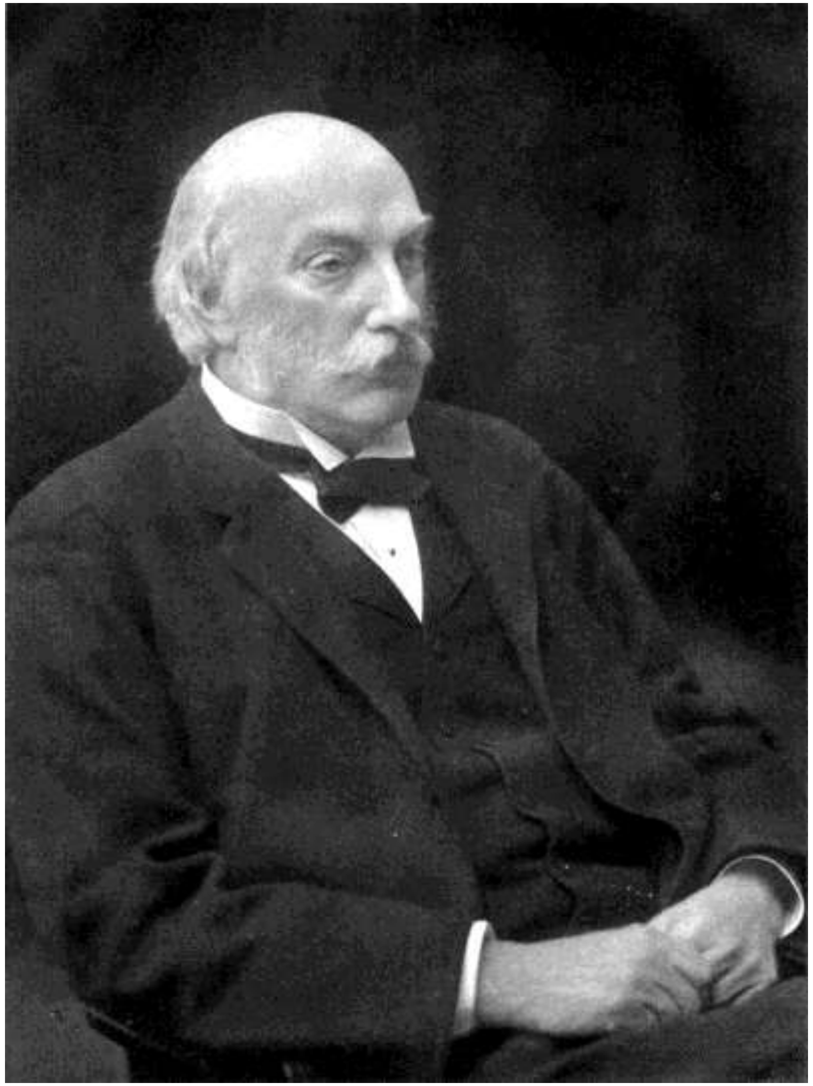
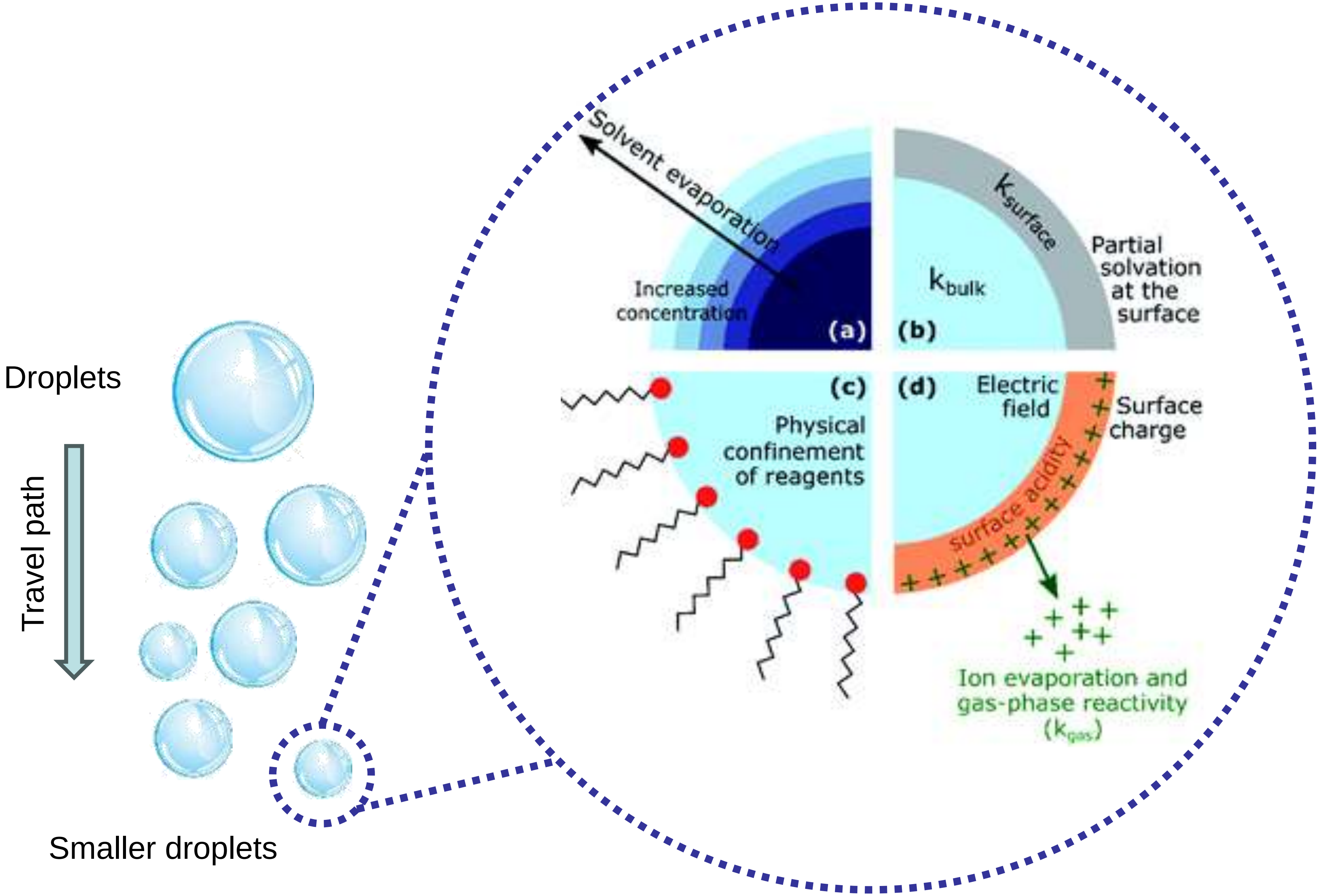


Image from Wikipedia

Understanding Microdroplets

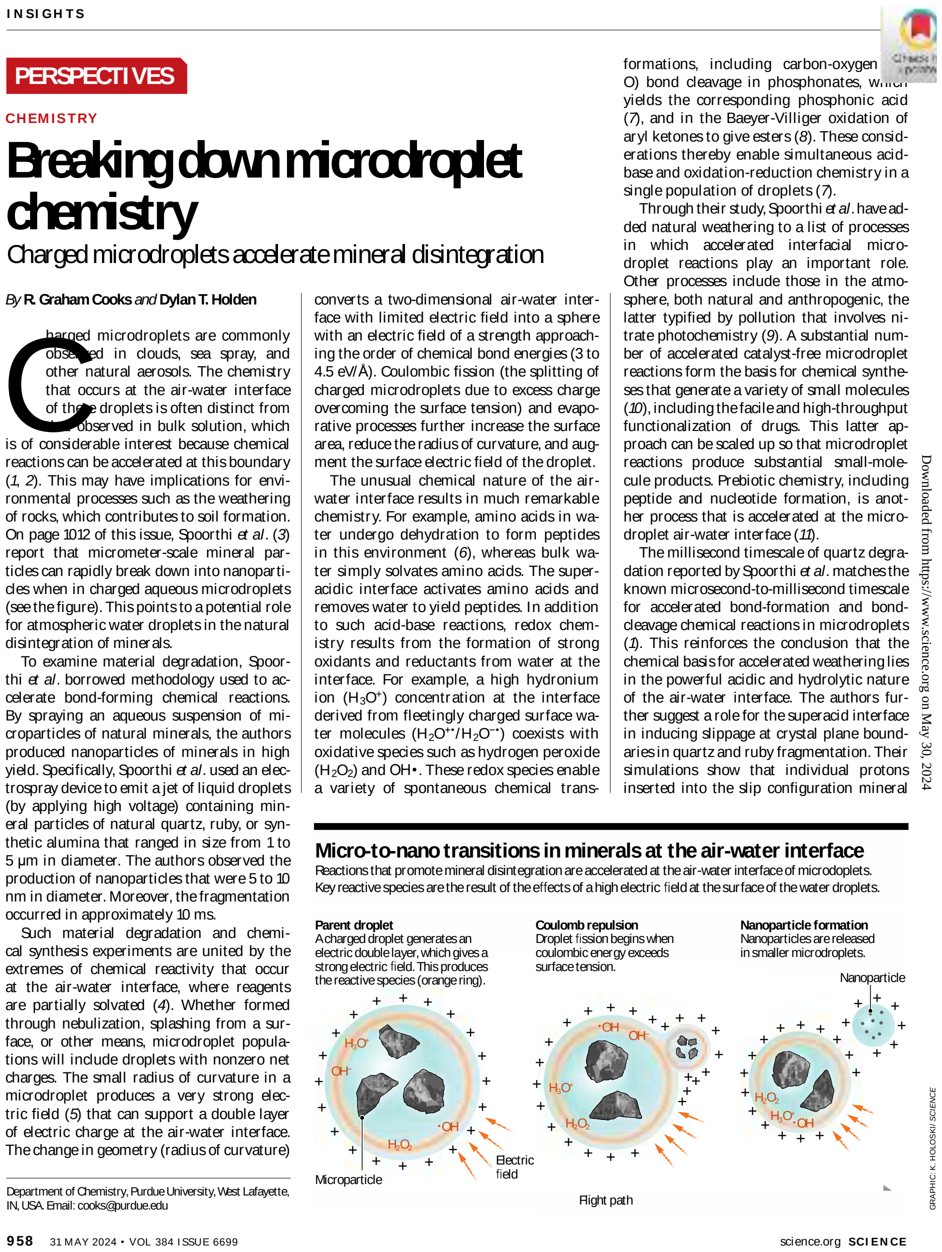


Droplets

Travel path

Smaller droplets

Grazia Rovelli, et. al. *Chem. Sci.*, 2020, 11, 13026–13043.



PERSPECTIVES

CHEMISTRY

Breaking down microdroplet chemistry

Charged microdroplets accelerate mineral disintegration

By **R. Graham Cooks** *and* **Dylan T. Holden**

Charged microdroplets are commonly observed in clouds, sea spray, and other natural aerosols. The chemistry that occurs at the air-water interface of these droplets is often distinct from that observed in bulk solution, which is of considerable interest because chemical reactions can be accelerated at this boundary (*1*, *2*). This may have implications for environmental processes such as the weathering of rocks, which contributes to soil formation. On page 1012 of this issue, Spoorthi *et al*. (*3*) report that micrometer-scale mineral particles can rapidly break down into nanoparticles when in charged aqueous microdroplets (see the figure). This points to a potential role for atmospheric water droplets in the natural disintegration of minerals.

To examine material degradation, Spoorthi *et al*. borrowed methodology used to accelerate bond-forming chemical reactions. By spraying an aqueous suspension of microparticles of natural minerals, the authors produced nanoparticles of minerals in high yield. Specifically, Spoorthi *et al*. used an electrospray device to emit a jet of liquid droplets (by applying high voltage) containing mineral particles of natural quartz, ruby, or synthetic alumina that ranged in size from 1 to 5 µm in diameter. The authors observed the production of nanoparticles that were 5 to 10 nm in diameter. Moreover, the fragmentation occurred in approximately 10 ms.

Such material degradation and chemical synthesis experiments are united by the extremes of chemical reactivity that occur at the air-water interface, where reagents are partially solvated (*4*). Whether formed through nebulization, splashing from a surface, or other means, microdroplet populations will include droplets with nonzero net charges. The small radius of curvature in a microdroplet produces a very strong electric field (*5*) that can support a double layer of electric charge at the air-water interface. The change in geometry (radius of curvature) converts a two-dimensional air-water interface with limited electric field into a sphere with an electric field of a strength approaching the order of chemical bond energies (3 to 4.5 eV/Å). Coulombic fission (the splitting of charged microdroplets due to excess charge overcoming the surface tension) and evaporative processes further increase the surface area, reduce the radius of curvature, and augment the surface electric field of the droplet.

The unusual chemical nature of the air-water interface results in much remarkable chemistry. For example, amino acids in water undergo dehydration to form peptides in this environment (*6*), whereas bulk water simply solvates amino acids. The superacidic interface activates amino acids and removes water to yield peptides. In addition to such acid-base reactions, redox chemistry results from the formation of strong oxidants and reductants from water at the interface. For example, a high hydronium ion (H_3O^+) concentration at the interface derived from fleetingly charged surface water molecules ($H_2O^{+\bullet}/H_2O^{-\bullet}$) coexists with oxidative species such as hydrogen peroxide (H_2O_2) and OH•. These redox species enable a variety of spontaneous chemical transformations, including carbon-oxygen O) bond cleavage in phosphonates, which yields the corresponding phosphonic acid (*7*), and in the Baeyer-Villiger oxidation of aryl ketones to give esters (*8*). These considerations thereby enable simultaneous acid-base and oxidation-reduction chemistry in a single population of droplets (*7*).

Through their study, Spoorthi *et al*. have added natural weathering to a list of processes in which accelerated interfacial microdroplet reactions play an important role. Other processes include those in the atmosphere, both natural and anthropogenic, the latter typified by pollution that involves nitrate photochemistry (*9*). A substantial number of accelerated catalyst-free microdroplet reactions form the basis for chemical syntheses that generate a variety of small molecules (*10*), including the facile and high-throughput functionalization of drugs. This latter approach can be scaled up so that microdroplet reactions produce substantial small-molecule products. Prebiotic chemistry, including peptide and nucleotide formation, is another process that is accelerated at the microdroplet air-water interface (*11*).

The millisecond timescale of quartz degradation reported by Spoorthi *et al*. matches the known microsecond-to-millisecond timescale for accelerated bond-formation and bond-cleavage chemical reactions in microdroplets (*1*). This reinforces the conclusion that the chemical basis for accelerated weathering lies in the powerful acidic and hydrolytic nature of the air-water interface. The authors further suggest a role for the superacid interface in inducing slippage at crystal plane boundaries in quartz and ruby fragmentation. Their simulations show that individual protons inserted into the slip configuration mineral

Micro-to-nano transitions in minerals at the air-water interface

Reactions that promote mineral disintegration are accelerated at the air-water interface of microdoplets. Key reactive species are the result of the effects of a high electric field at the surface of the water droplets.

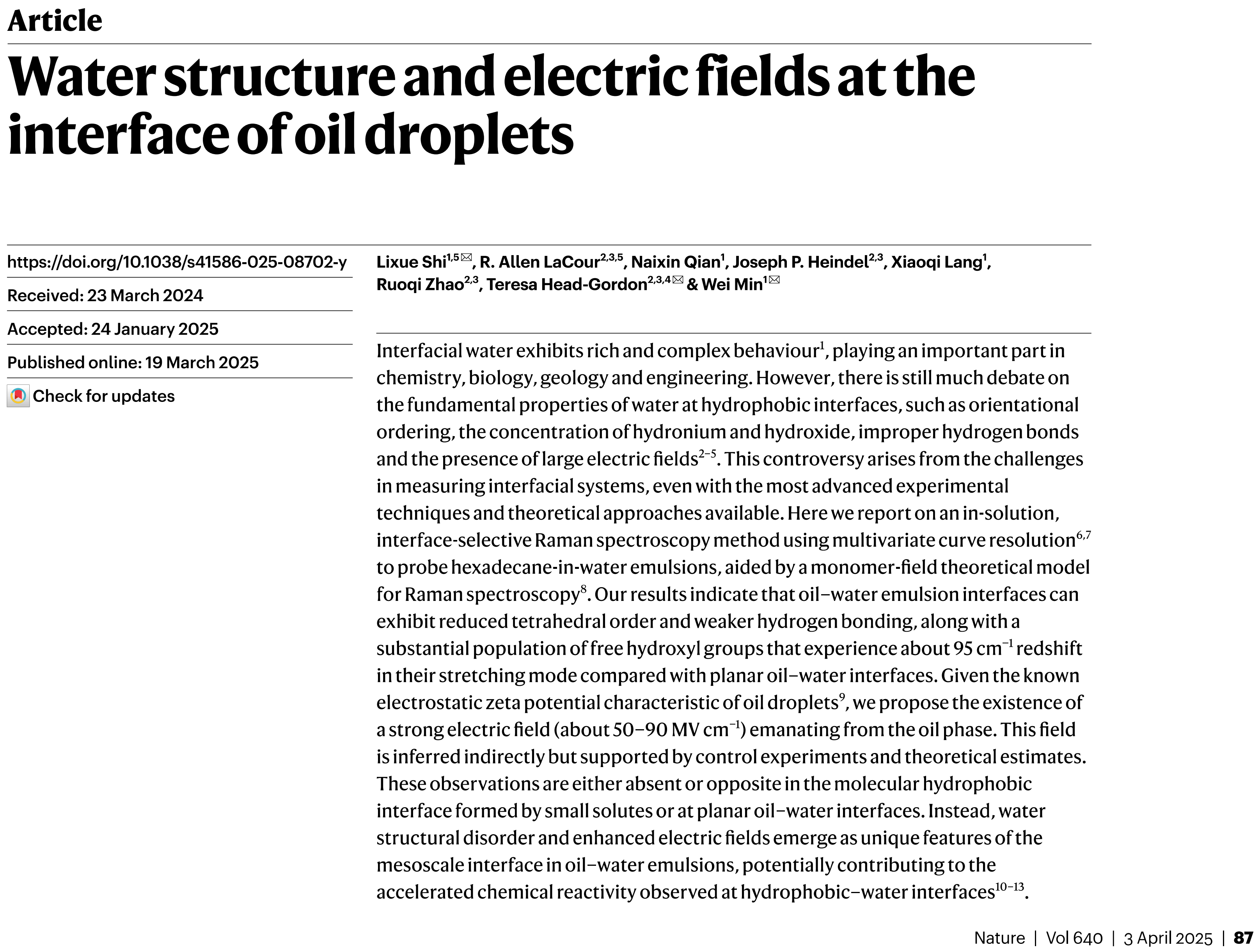
Parent droplet
A charged droplet generates an electric double layer, which gives a strong electric field. This produces the reactive species (orange ring).

Coulomb repulsion
Droplet fission begins when coulombic energy exceeds surface tension.

Nanoparticle formation
Nanoparticles are released in smaller microdroplets.

GRAPHIC: K. HOLOSKI/ *SCIENCE*

Department of Chemistry, Purdue University, West Lafayette, IN, USA. Email: cooks@purdue.edu



Article

Water structure and electric fields at the interface of oil droplets

https://doi.org/10.1038/s41586-025-08702-y

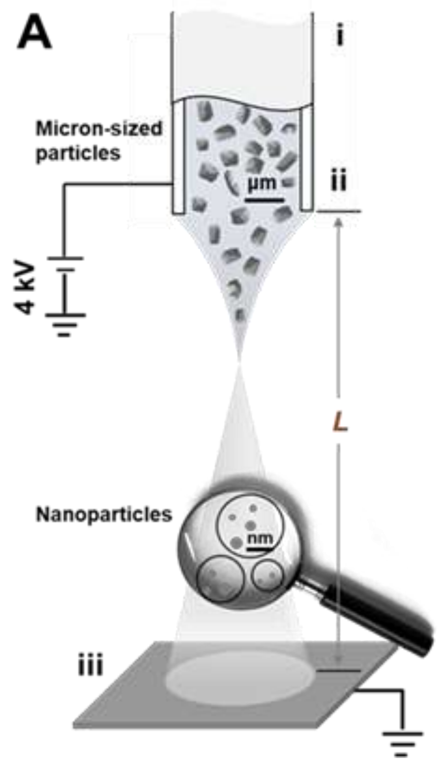
Received: 23 March 2024

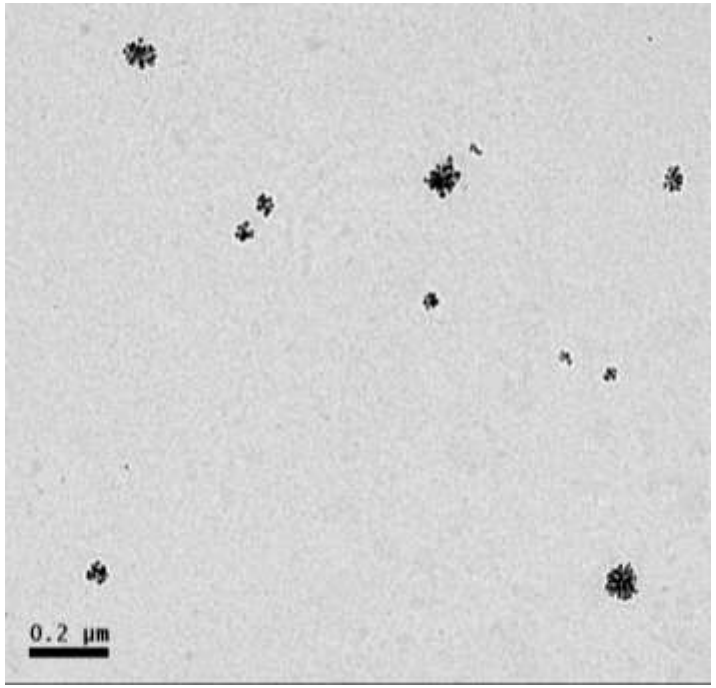
Accepted: 24 January 2025

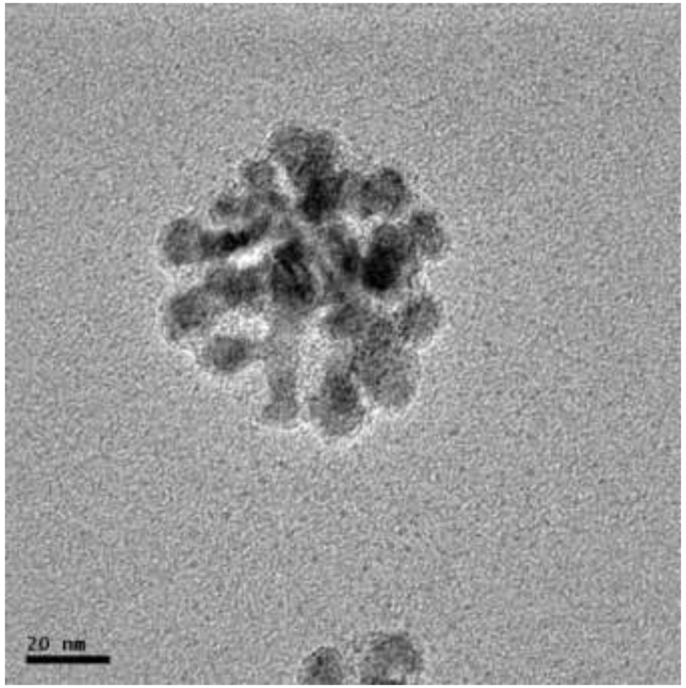
Lixue Shi[1,5]✉, R. Allen LaCour[2,3,5], Naixin Qian[1], Joseph P. Heindel[2,3], Xiaoqi Lang[1], Ruoqi Zhao[2,3], Teresa Head-Gordon[2,3,4]✉ & Wei Min[1]✉

Interfacial water exhibits rich and complex behaviour[1], playing an important part in chemistry, biology, geology and engineering. However, there is still much debate on the fundamental properties of water at hydrophobic interfaces, such as orientational ordering, the concentration of hydronium and hydroxide, improper hydrogen bonds and the presence of large electric fields[2–5]. This controversy arises from the challenges in measuring interfacial systems, even with the most advanced experimental techniques and theoretical approaches available. Here we report on an in-solution, interface-selective Raman spectroscopy method using multivariate curve resolution[6,7] to probe hexadecane-in-water emulsions, aided by a monomer-field theoretical model for Raman spectroscopy[8]. Our results indicate that oil–water emulsion interfaces can exhibit reduced tetrahedral order and weaker hydrogen bonding, along with a substantial population of free hydroxyl groups that experience about 95 cm^{-1} redshift in their stretching mode compared with planar oil–water interfaces. Given the known electrostatic zeta potential characteristic of oil droplets[9], we propose the existence of a strong electric field (about 50–90 MV cm^{-1}) emanating from the oil phase. This field is inferred indirectly but supported by control experiments and theoretical estimates. These observations are either absent or opposite in the molecular hydrophobic interface formed by small solutes or at planar oil–water interfaces. Instead, water structural disorder and enhanced electric fields emerge as unique features of the mesoscale interface in oil–water emulsions, potentially contributing to the accelerated chemical reactivity observed at hydrophobic–water interfaces[10–13].

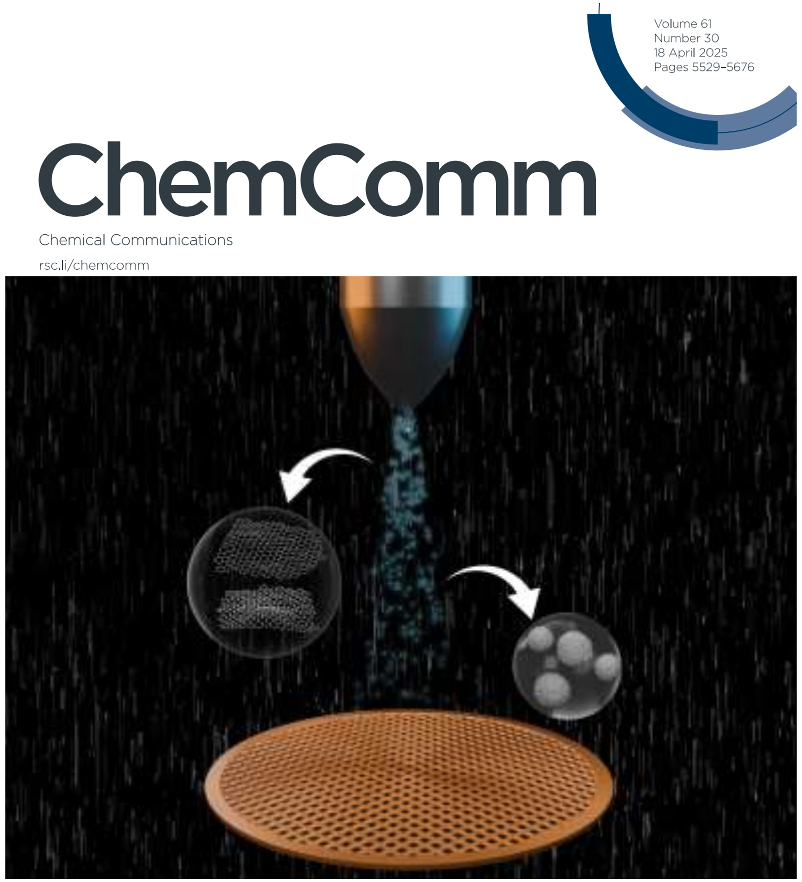
How do they form?





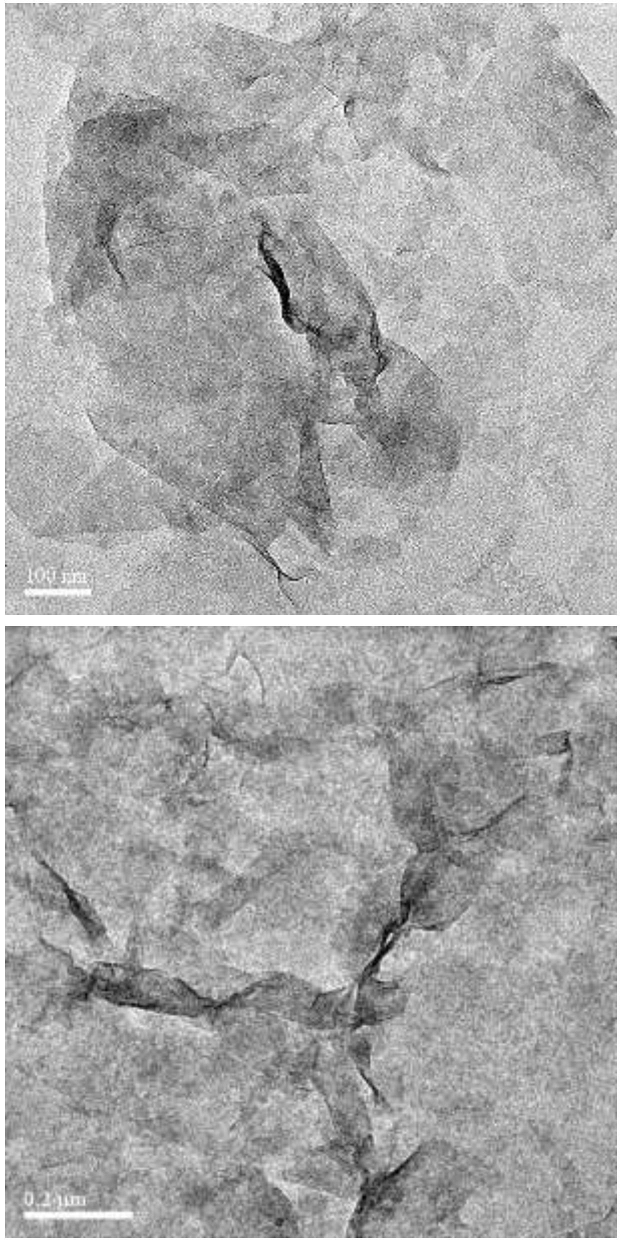


MoS_2 Nanosheets

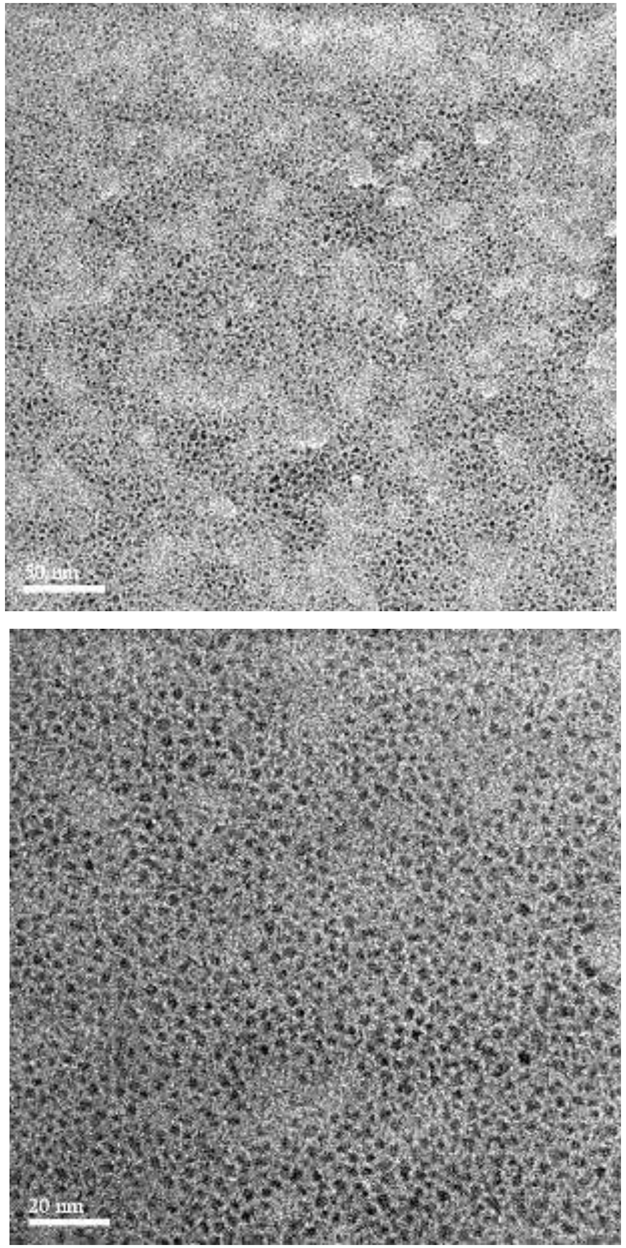


Volume 61
Number 30
18 April 2025
Pages 5529–5676

ChemComm
Chemical Communications
rsc.li/chemcomm

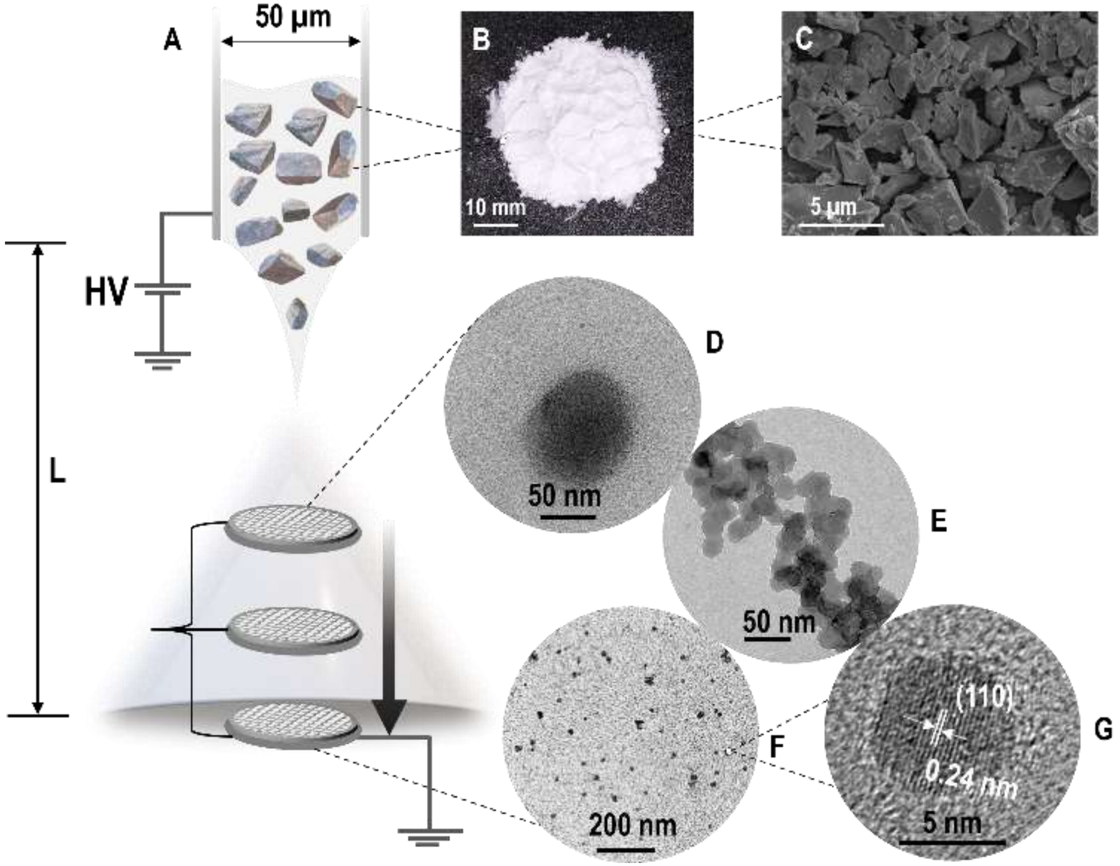


MoS_2 Nanosheet



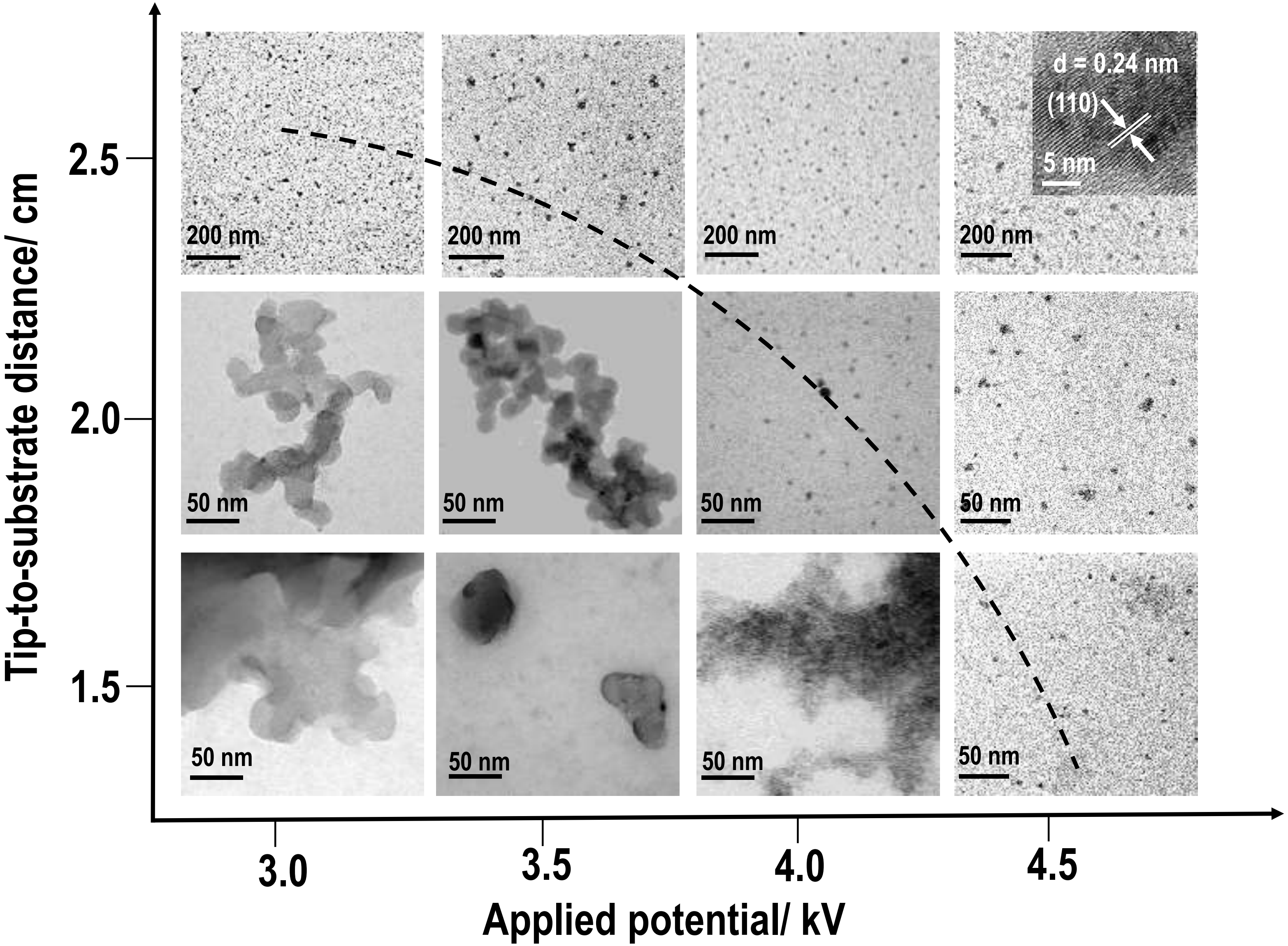
MoS_2 Nanoparticles

Unveiling steps in the weathering of minerals



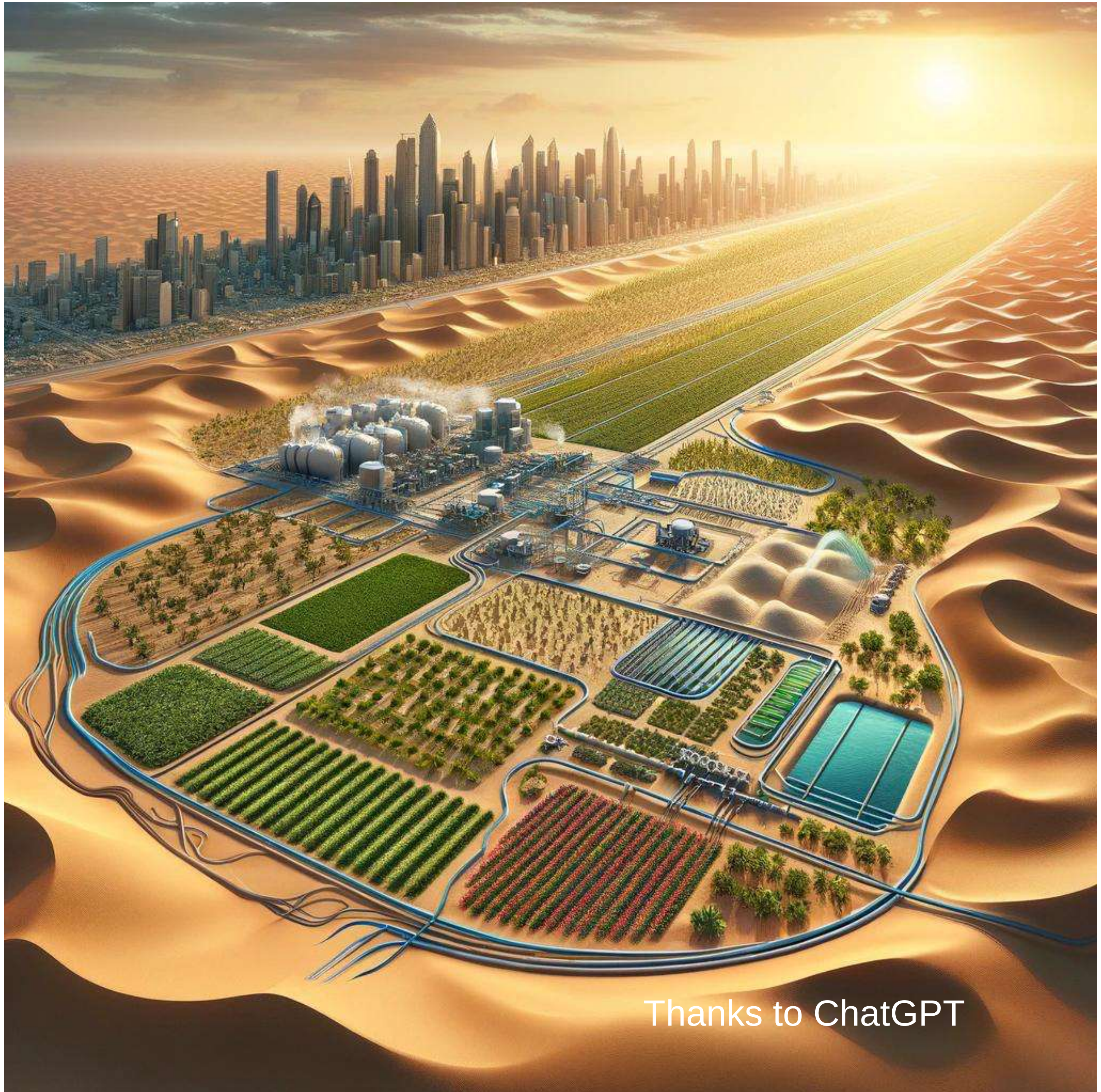
Anubhav Mahapatra et al, Submitted

Disintegration of quartz



Vision

Make soil using processed wastewater and make deserts bloom.



Thanks to ChatGPT

Conclusions

Natural minerals break spontaneously in charged water microdroplets
It occurs only in water… so far
Studies on a variety of materials
Facile due to proton-induced slip
Detailed investigations are essential to know more
Implications to the production of specific nanomaterials and soil in general

Department of Science and Technology

Institute of Eminence

Indian Institute of Technology Madras

Bhaskar Ramamurthi/V. Kamakoti

Thank you all

pradeep RESEARCH GROUP

THEMATIC UNIT OF EXCELLENCE