The physics of clay minerals: From the nano-scale to the geo-scale, and everything in between

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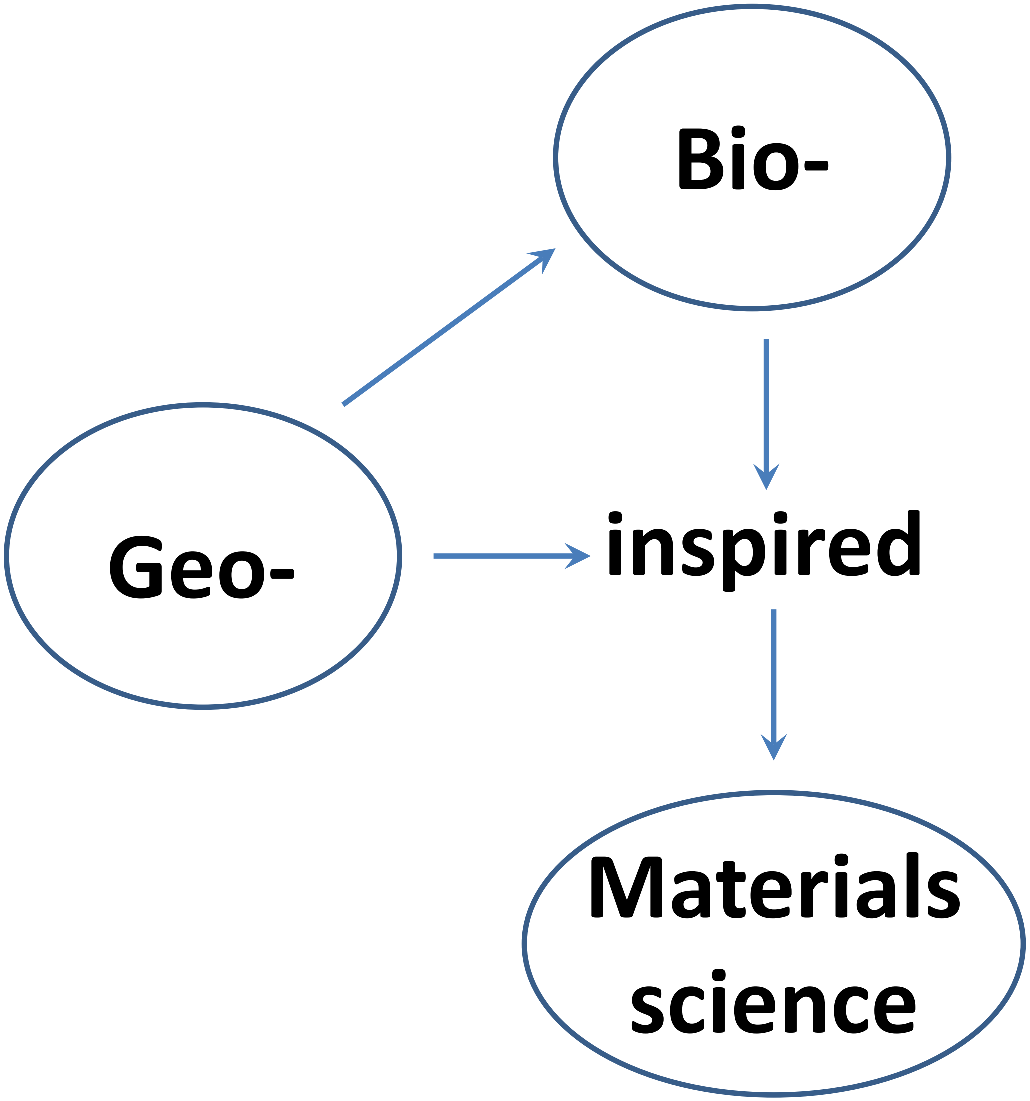
NORWAY


Bio-
Geo-
inspired
Materials
science

Question:

What is the first that comes to your mind when I say the word: Clay?


MUD?

Clays in ART

The oldest surviving piece of art:

The oldest sample known of baked clay:

Figurine: "Venus of Vestonice"

Found in 1920 in the Czech Republic.

Approximate age: 23000 B.C.
(Dated from mammoth bone ash in the clay)

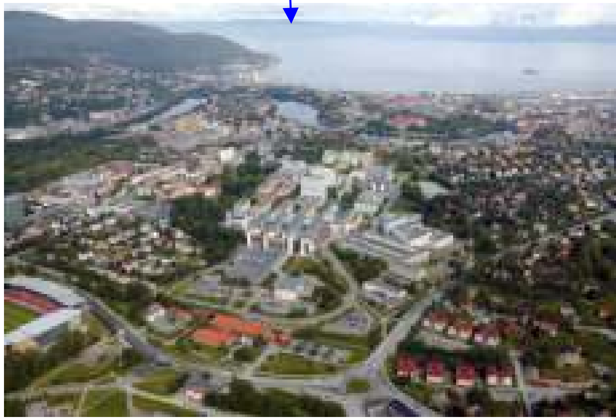
Clay avalanches

Clay avalanche: Rissa Norway 1978

Observation: Extreme mechanical instability of certain clayey soils, under given humidity conditions

Example: the Rissa landslide (1978, near Trondheim, Norway)

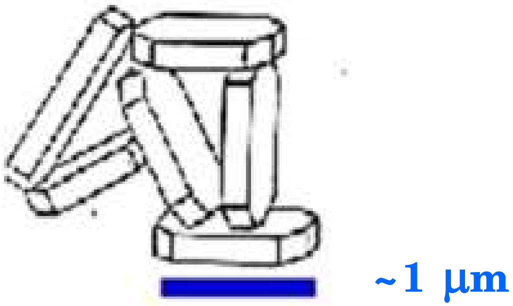
- Triggered by the excavation of 1000 m^3 prior to building a barn
- Duration: 6 min
- 7 to 8 millions m^3 of soil were displaced
- 40 persons were taken, 1 died
- 7 farms were rammed
- 33 ha of lands were touched
- A linear length of 80 m of coast ended up in the fjord
- The slope was very moderate



The natural quick clays were sedimented at the end of the last ice age, commonly at river mouths in salty water.

The specificity of the natural quick clays is that the salt has been washed away by water over time, which has weakened the cohesion of the material.

“House of card” structure?



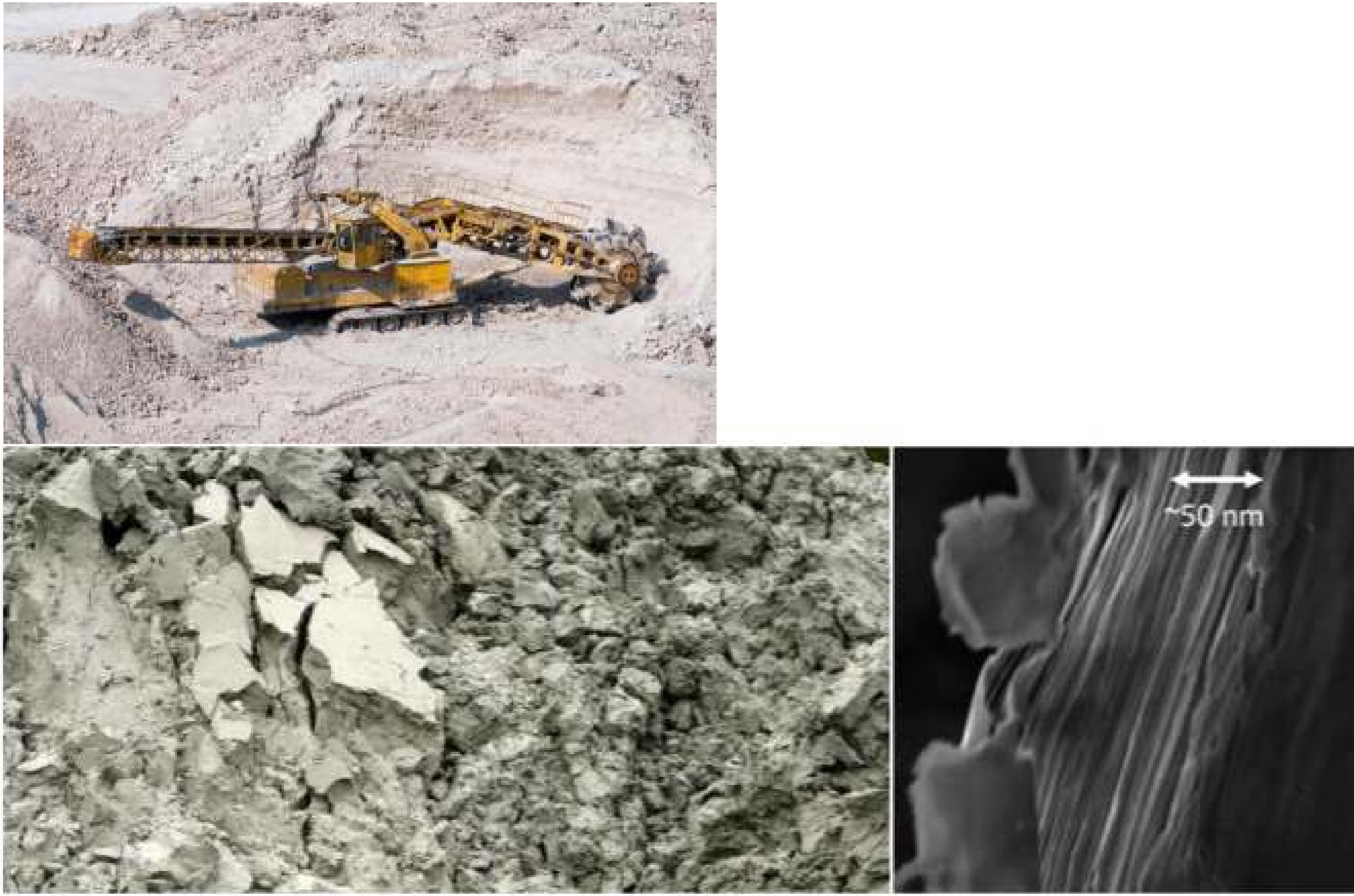
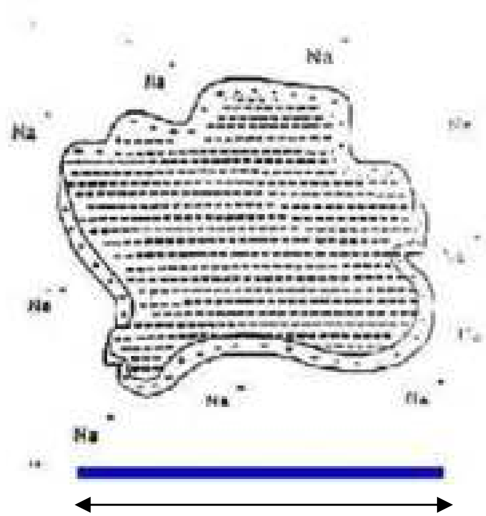


Figure 1 *The left panel above is from a natural clay deposit, and it illustrates on a macroscopic scale that clays are anisotropic materials. The right panel is an electron microscope image of vermiculite clay demonstrating its lamellar structure on the nano-scale, reminiscent of graphene, which is one of the main characteristics of clay minerals.*

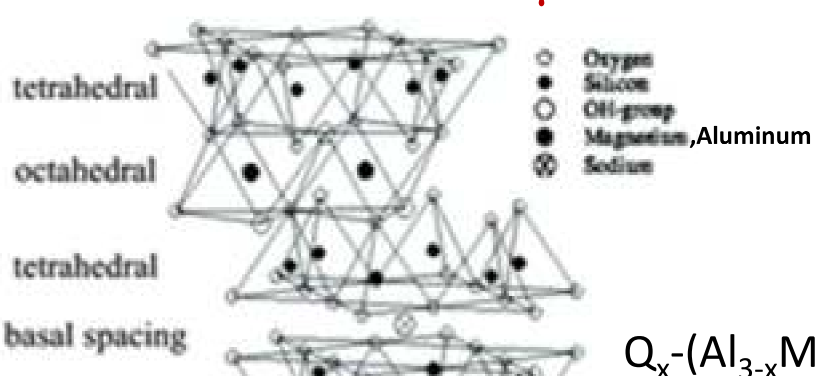
Clays are nano-/micro-particles:

Two basic forms at nano-/micro-scale:

1 nm thick "nanocards" (Bentonite/Laponite)

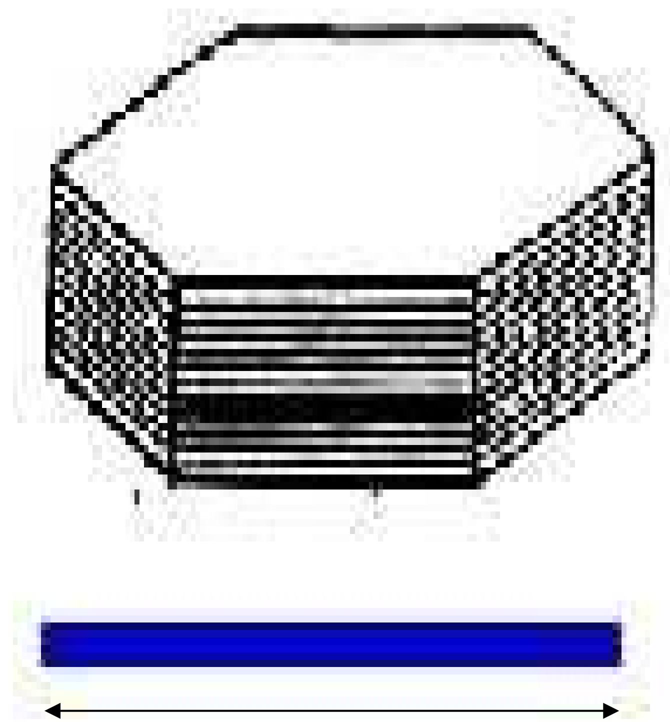


~ μm



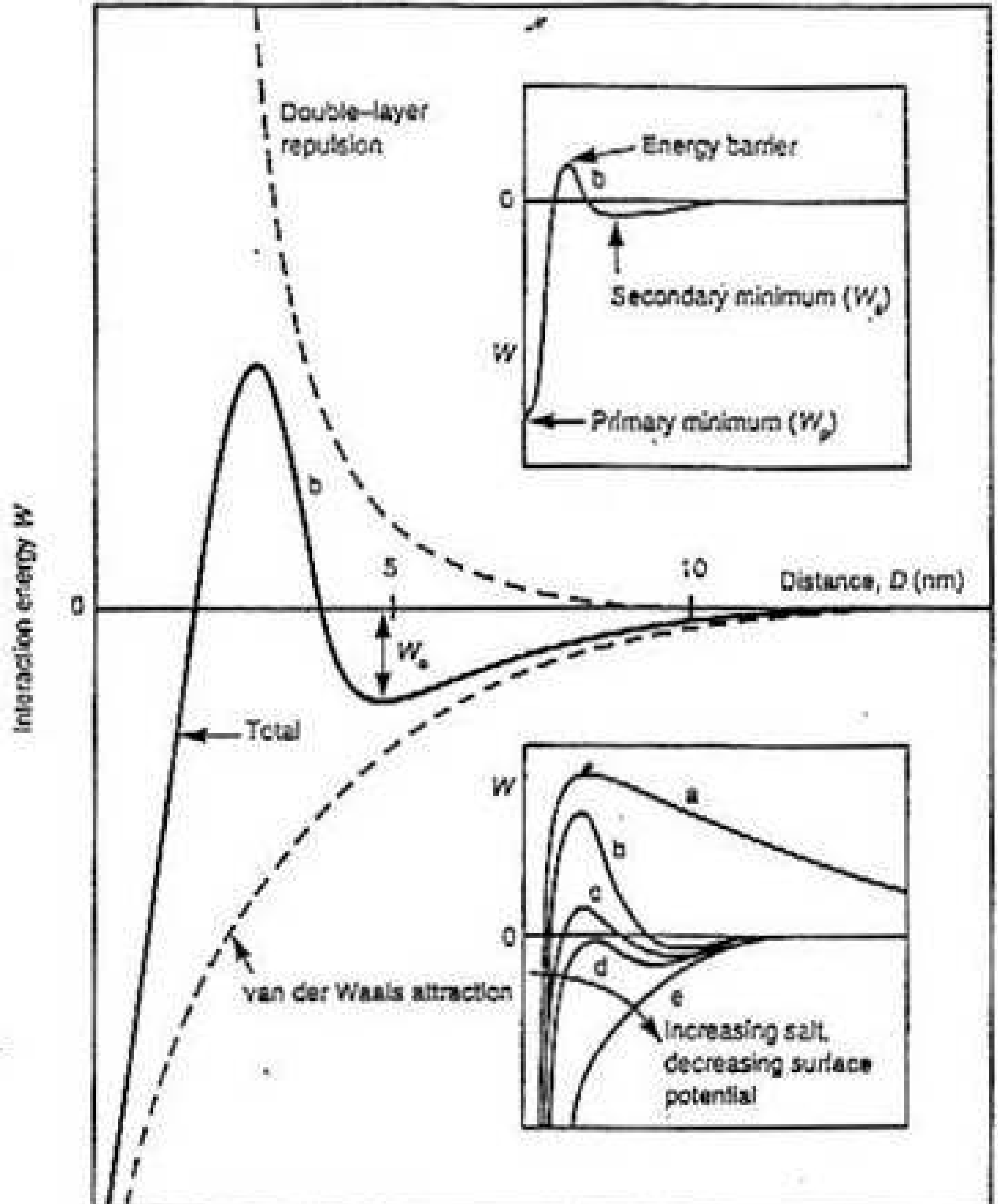
$Q_x\text{-}(Al_{3-x}Mg_x)Si_4O_{10}(OH)_2$

100 nm thick nanolayered particles "decks of nanocards" (Kaolinite)



~ μm

DLVO Theory:
vdW
+ Screened Electrostatic Rep.



From J. Israelachvili

Temperature effects:

SCIENTIFIC REPORTS

WAXS + SAXS + Rheometry

OPEN

Swelling transition of a clay induced by heating

SUBJECT AREAS:
POLYMERS AND SOFT MATERIALS
MATERIALS PHYSICS
CHEMICAL PHYSICS
MINERALOGY

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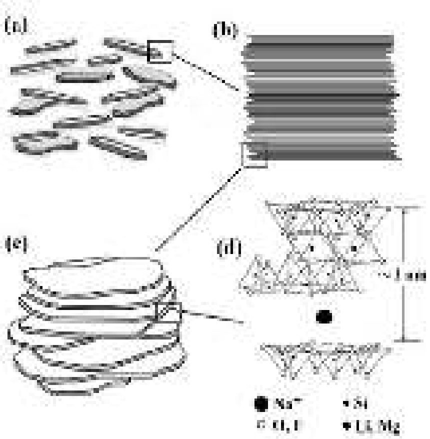
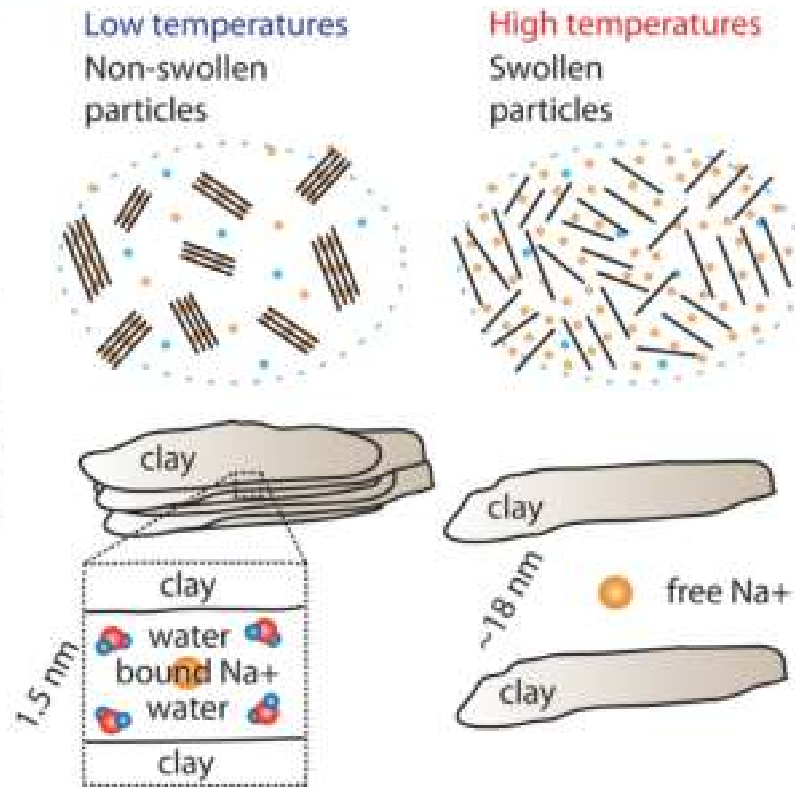
E. L. Hansen[1], H. Hemmen[1], D. M. Fonseca[1*], C. Coutant[2], K. D. Knudsen[3], T. S. Plivelic[4], D. Bonn[5] & J. O. Fossum[1,6]

[1]Department of Physics, Norwegian University of Science and Technology – NTNU, Trondheim, Norway, [2]UFR Structure et Propriétés de la Matière, Université de Rennes 1, Rennes, France, [3]Physics Department, Institute for Energy Technology – IFE, Kjeller, Norway, [4]MAX IV Laboratory, Lund University, Lund, Sweden, [5]Van der Waals-Zeeman Institute, University of Amsterdam, Amsterdam, Netherlands, [6]Centre for Advanced Study – CAS, Norwegian Academy of Science and Letters, Oslo, Norway.

Clays are of paramount importance for soil stability, but also in applications ranging from oil recovery to composites and hydrogels. Generically, clays are divided into two subclasses: macroscopically swelling, 'active' clays that have the capacity for taking up large amounts of water to form stable gels, and 'passive' or non-swelling clays; the former stabilize soils whereas the latter are known to lead to landslides. However, it has been unclear so far what mechanisms underlie clay swelling. Here, we report the first observation of a temperature-induced transition from a passive to an active, swelling clay. We propose a simple description of the swelling transition: while net attractive interactions are dominant at low temperatures so that the clay particles remain attached to each other in stacks, at higher temperatures it is energetically favourable for the clay to swell due to the entropy that is gained by counterions which are liberated during swelling.





Simple analog landslide experiments

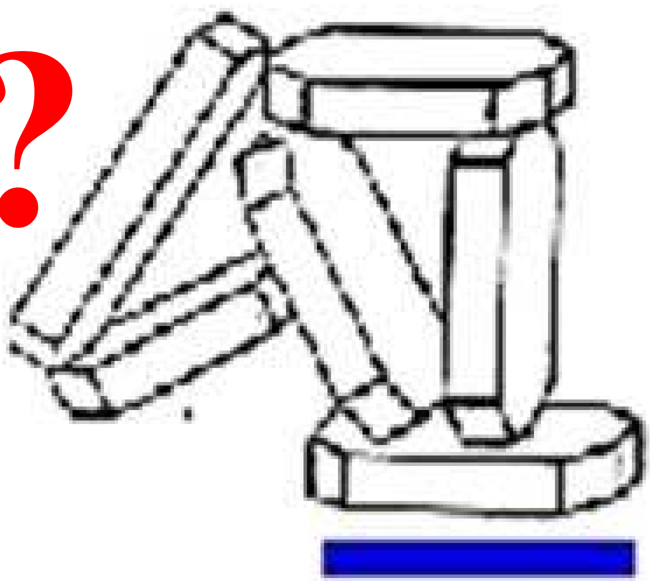
Quickclay and Landslides of Clayey Soils,
A.Khaldoun, P.Moller, A. Fall, G.Wegdam,B. De Leeuw, Y. Meheust, J.O. Fossum, D. Bonn,
Géosciences Rennes 1, University of Amsterdam, ENS-Paris, NTNU-Trondheim
Physical Review Letters 103, 188301 (2009)

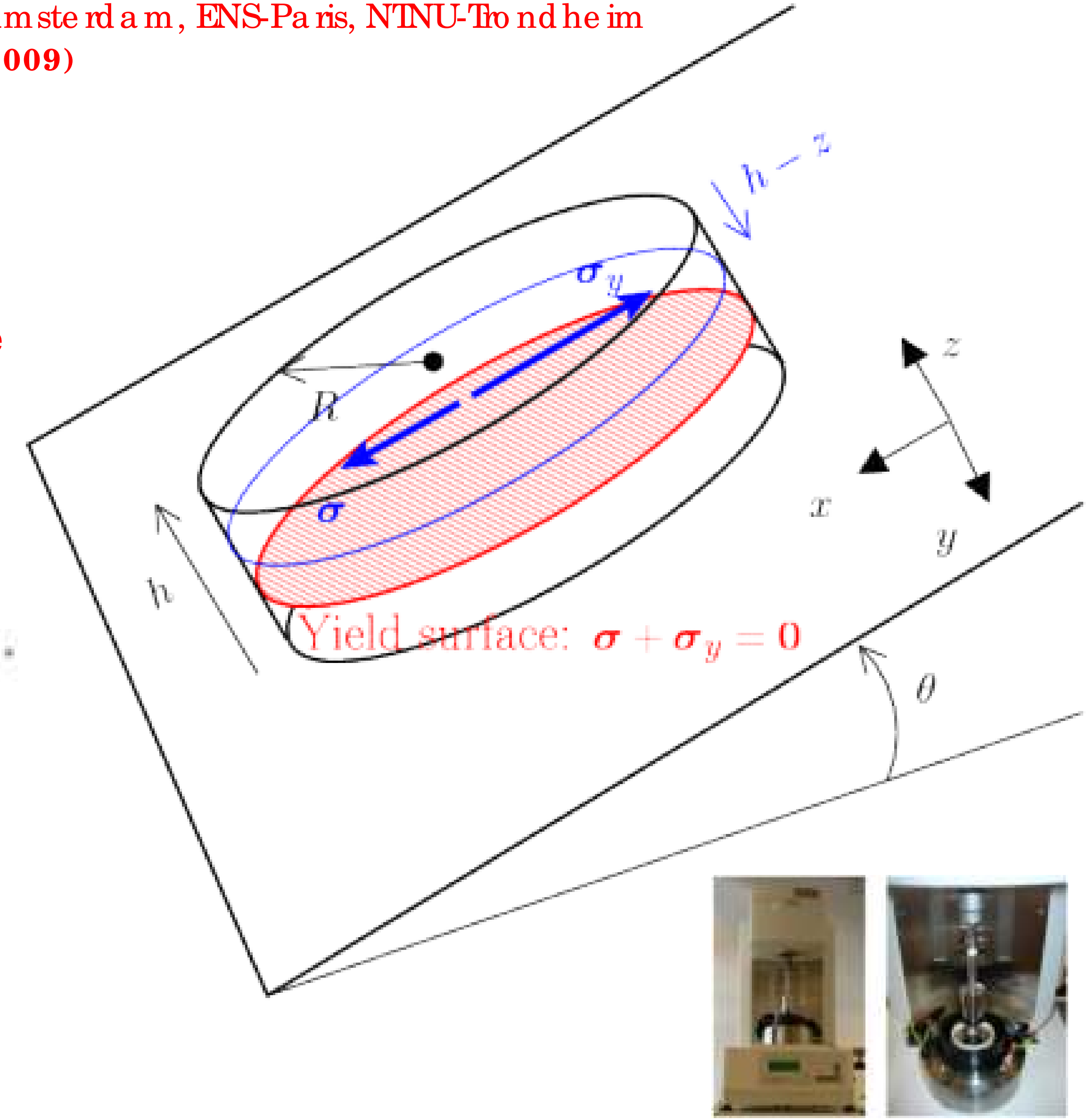
$$\sigma(z) = \rho g (h - z) \sin\theta$$

(null at the free surface)

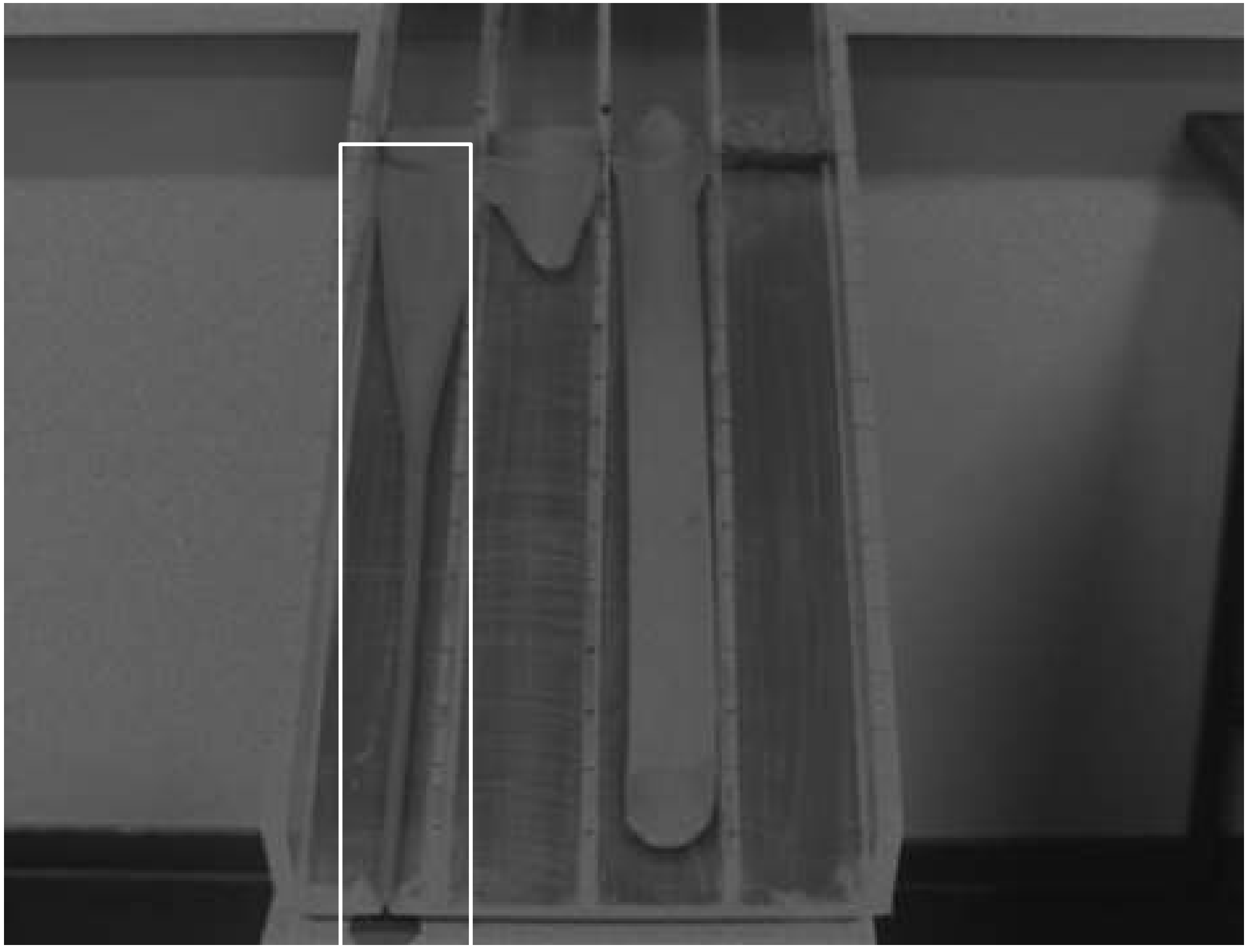
All material above the yield surface
is expected to flow

?





Analog laboratory landslide experiments

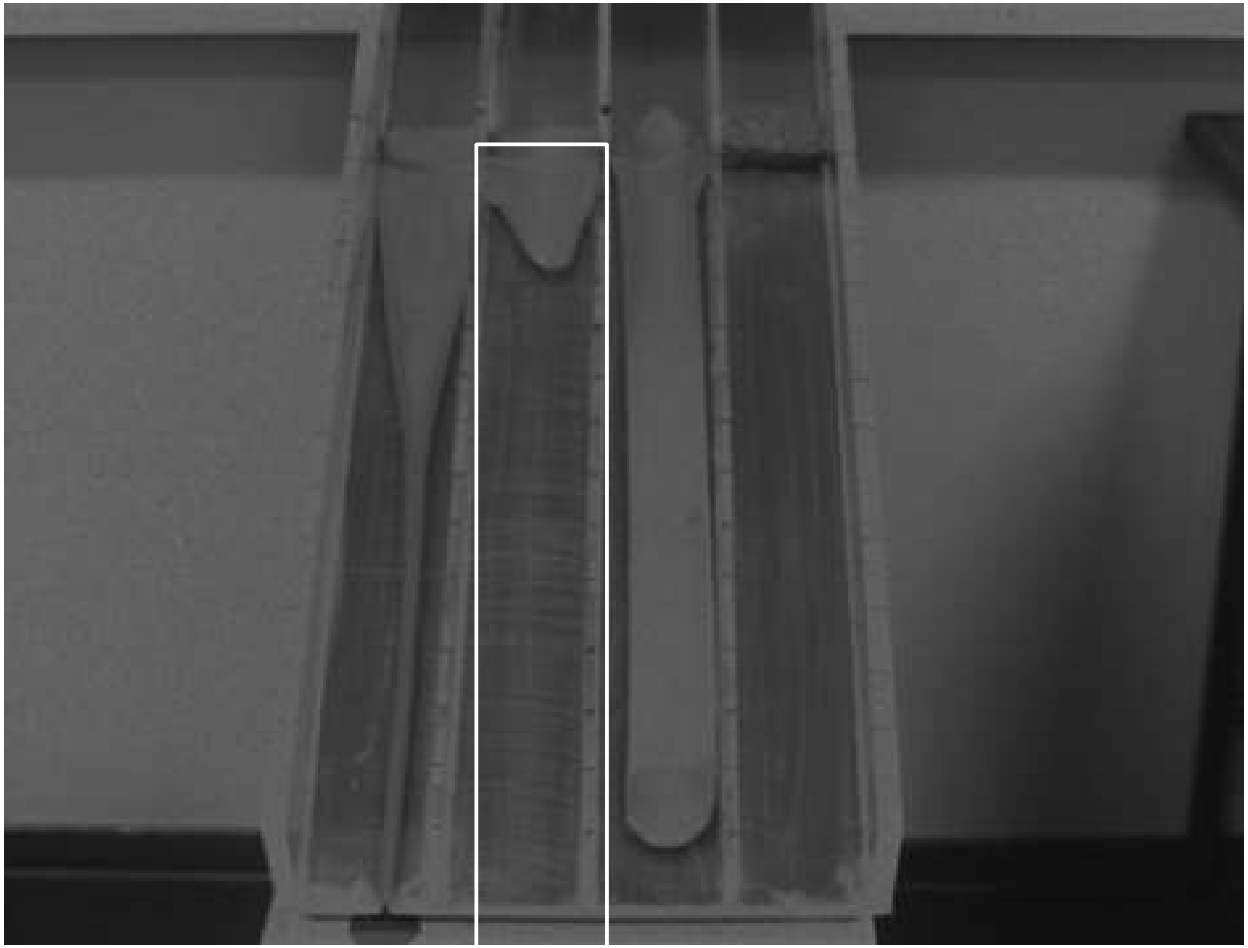


56% 58% 61% 63%

Weight% clay

Quasi-newtonian flow

Analog laboratory landslide experiments (3)

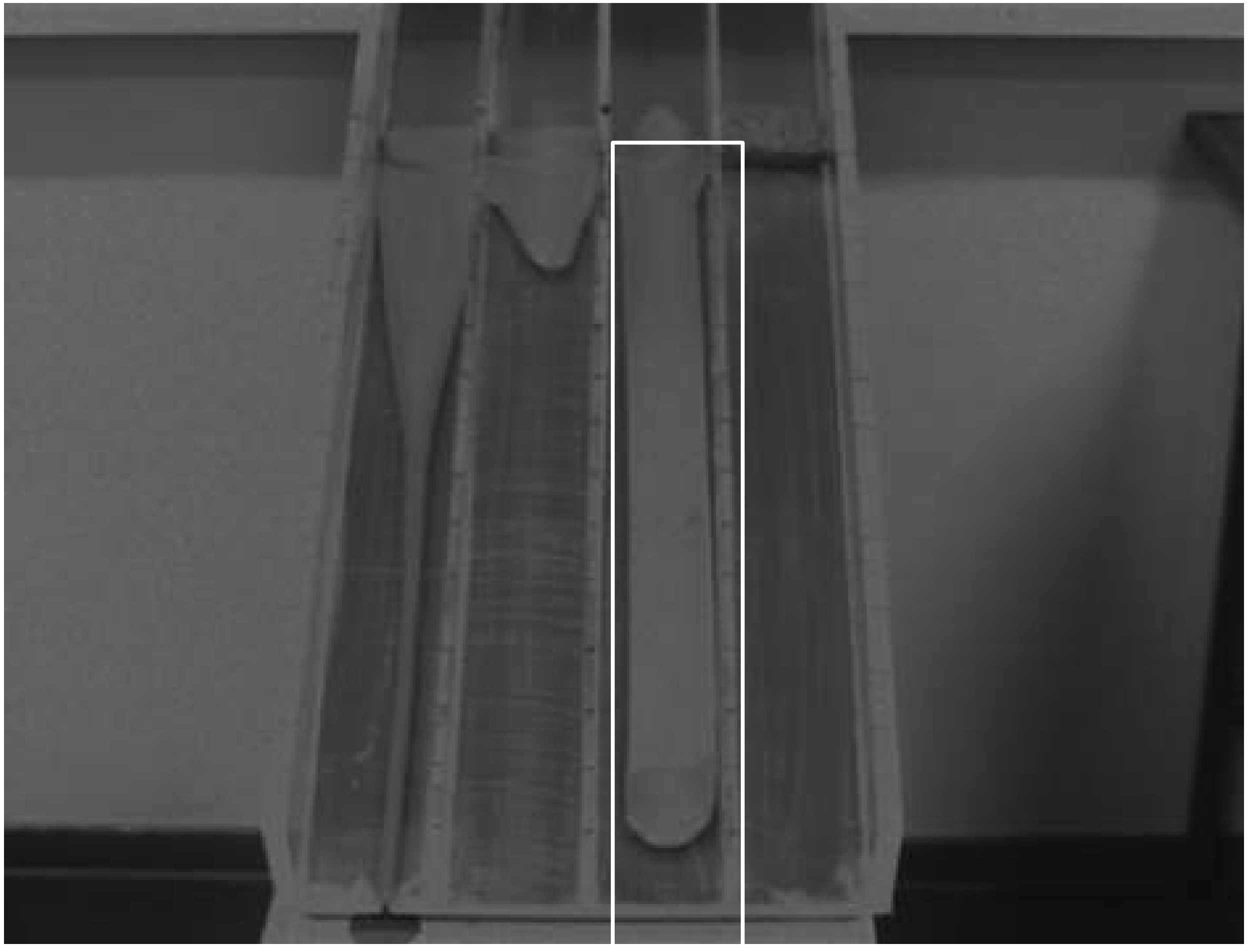


56% 58% 61% 63%

Weight% clay

Yield stress fluid flow

Analog laboratory landslide experiments



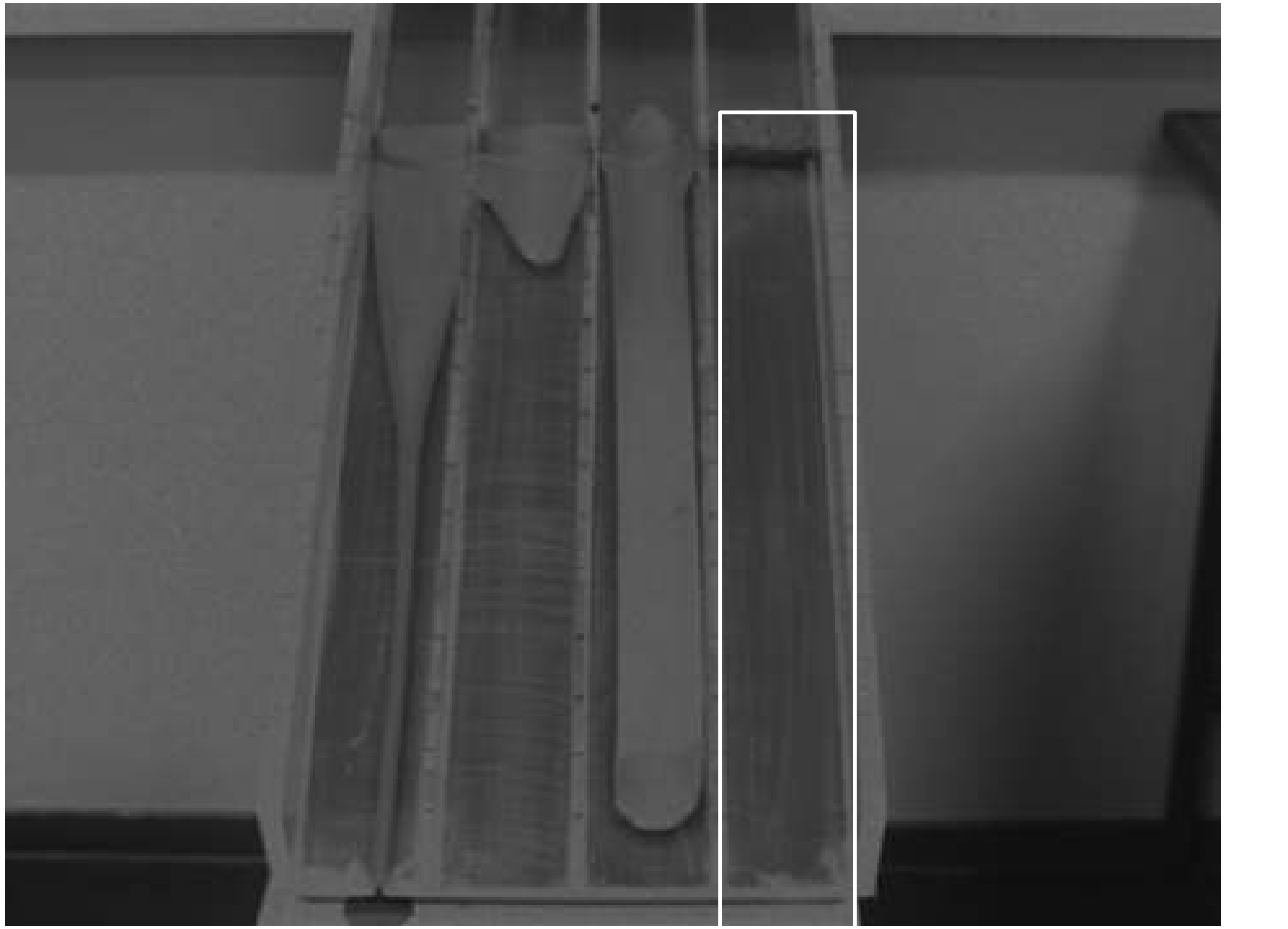
56% 58% 61% 63%

Weight% clay

Landslide regime = flow on a **thin lubrication layer**

⇒ This is why the Rissa farm buildings remained upright

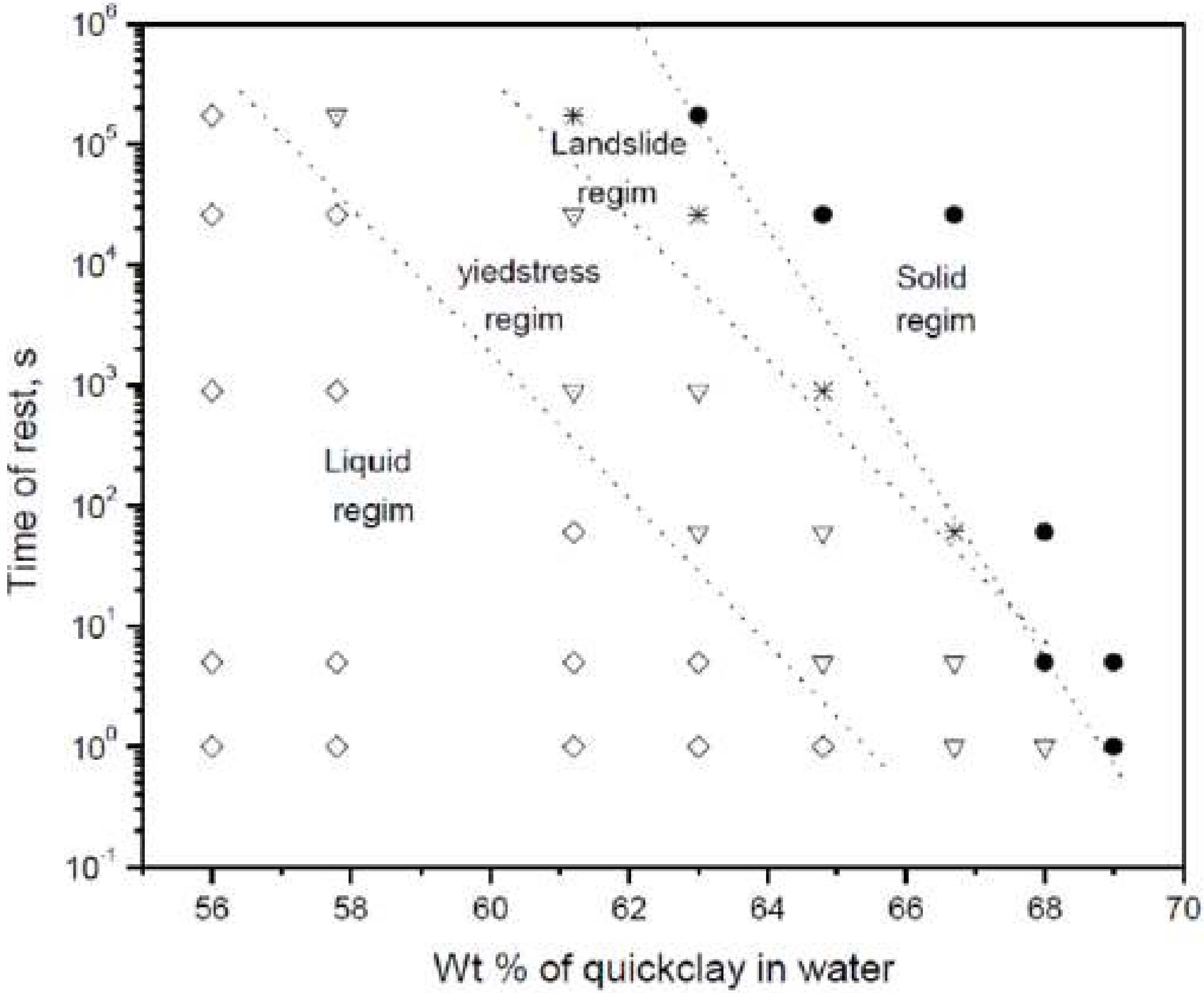
Analog laboratory landslide experiments



56% 58% 61% 63%

Weight% clay

No flow:
steric hindrance of particle alignment?



Similar to that observed in earlier study on bentonite/montmorillonite muds (Coussot, P., N. Roussel, S. Jarny, and H. Chanson: Continous or catastrophic solid-liquid transition in jammed systems, Phys. Fluids, 17, 011,704 (2005))

In addition: Preparation of a synthetic quick clay

Composition: illite + bentonite + salt

Illite is washed to remove any salt
3% of washed bentonite (swelling clay)
Controlled addition of salt and measure of the elastic modulus as a function of the salt concentration

Our conclusions (so far) regarding quick clay materials science and avalanches:

→ A material containing more water is not necessarily more unstable

→ For a limited range of water contents, the slide can occur on a very thin lubrication layer (lubrication layer/threadmill effect)

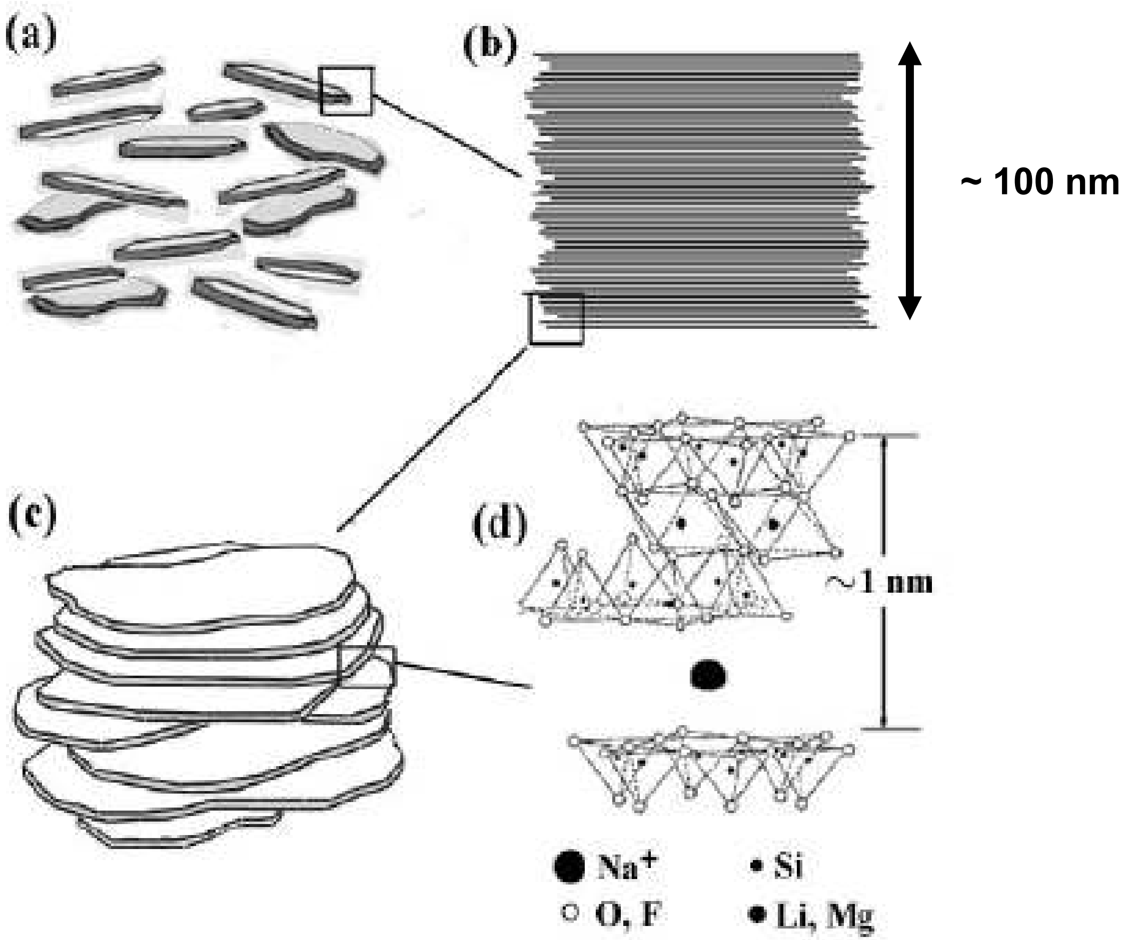
→This occurs when the material's yield stress is larger than a critical value that can be related to a simple theoretical model including the volume of the sample

→ It is possible to prepare in the laboratory a synthetic material that has the same mechanical properties as the natural quick clay: A small amount of swelling (smectite) clay is essential for the behavior observed

Appropriate question: Did we really study the “native” quick clay?

Our clay experimental model system:

Q-fluorohectorite synthetic clay: Q_x-$(Mg_{3-x}Li_x)Si_4O_{10}F_2$,
Q is the exchangeable cation (Q = Na^+, Li^+, Ni^{2+}, Fe^{3+}, etc)



One of our experiments:

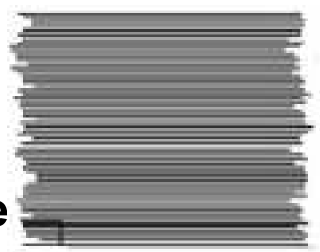
Orientational order in gravity dispersed clay colloids: A synchrotron x-ray scattering study of Na-fluorohectorite suspensions.
E. DiMasi, J.O. Fossum, T. Gog, and C. Venkataraman. **Phys.Rev. E64, 061704 (2001)**

Clay (Fluorohectorite)
powder
About 3 % in weight

Pure Water

NaCl
About 10^{-3} M

Basic clay particle



~100nm

~µm

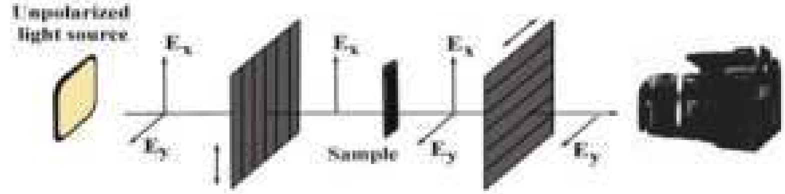
Liquid

Isotropic gel or glass?

Nematic like gel or glass?

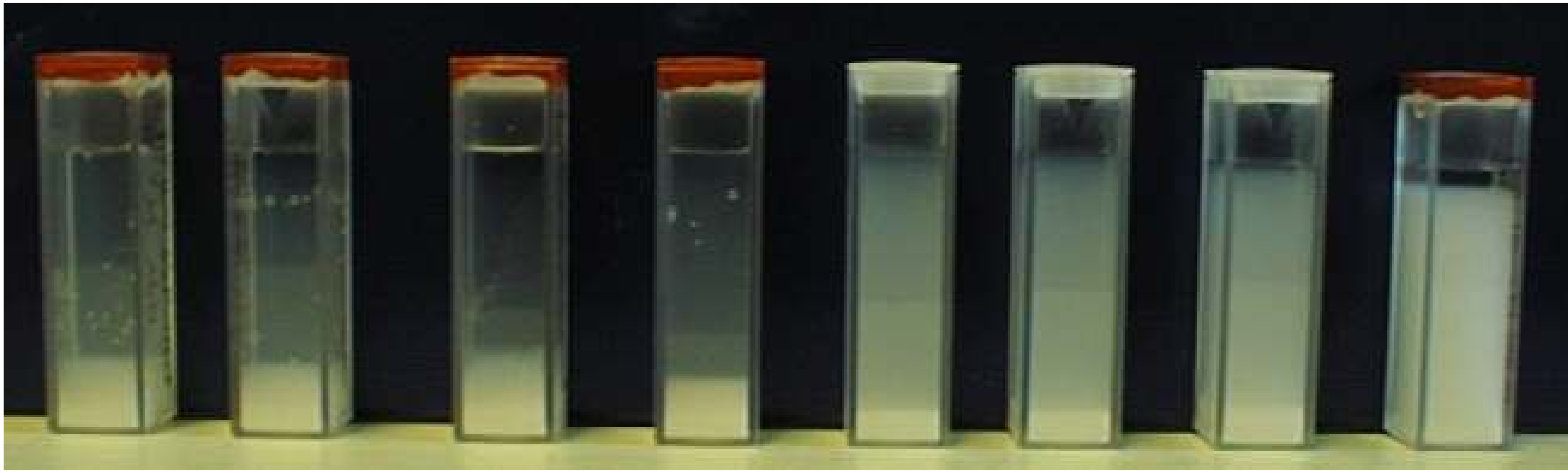
Sediment

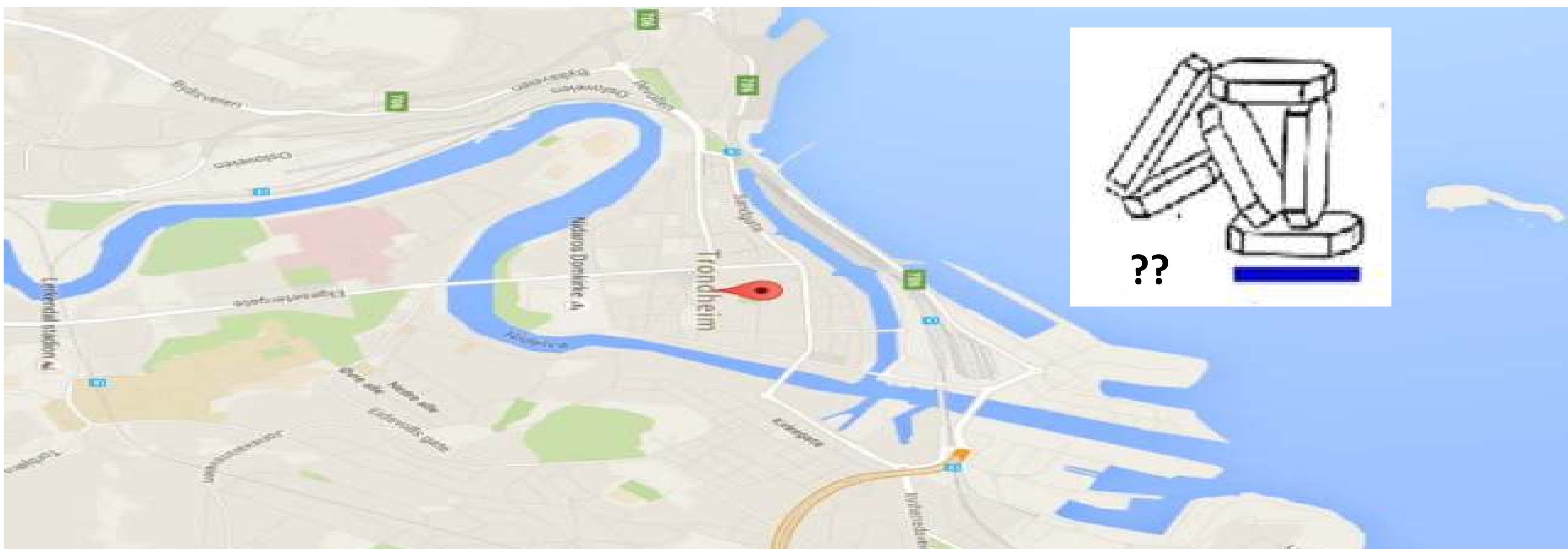
4 "Phases" in same Sample Tube



Self-organization by sedimentation clay particles in H_2O:

Increasing salt:





Clay avalanches connected to layered structures or or lubrication layer of house of cards?

Snow avalanches and weak layers:
All snow exists as layers. Some layers are relatively more cohesive (stronger layers) and others are relatively less cohesive (weaker layers).

When the snowpack is stressed by rapid changes (e.g. wind-drifted snow, new snow, or rain) this stress can cause the weak layer to fracture.

Liquid Crystalline Phases Characterization

Order Parameter = O.P.
= Angular distribution function
= $S_2 = \frac{1}{2}\langle 3\cos^2\theta - 1 \rangle$

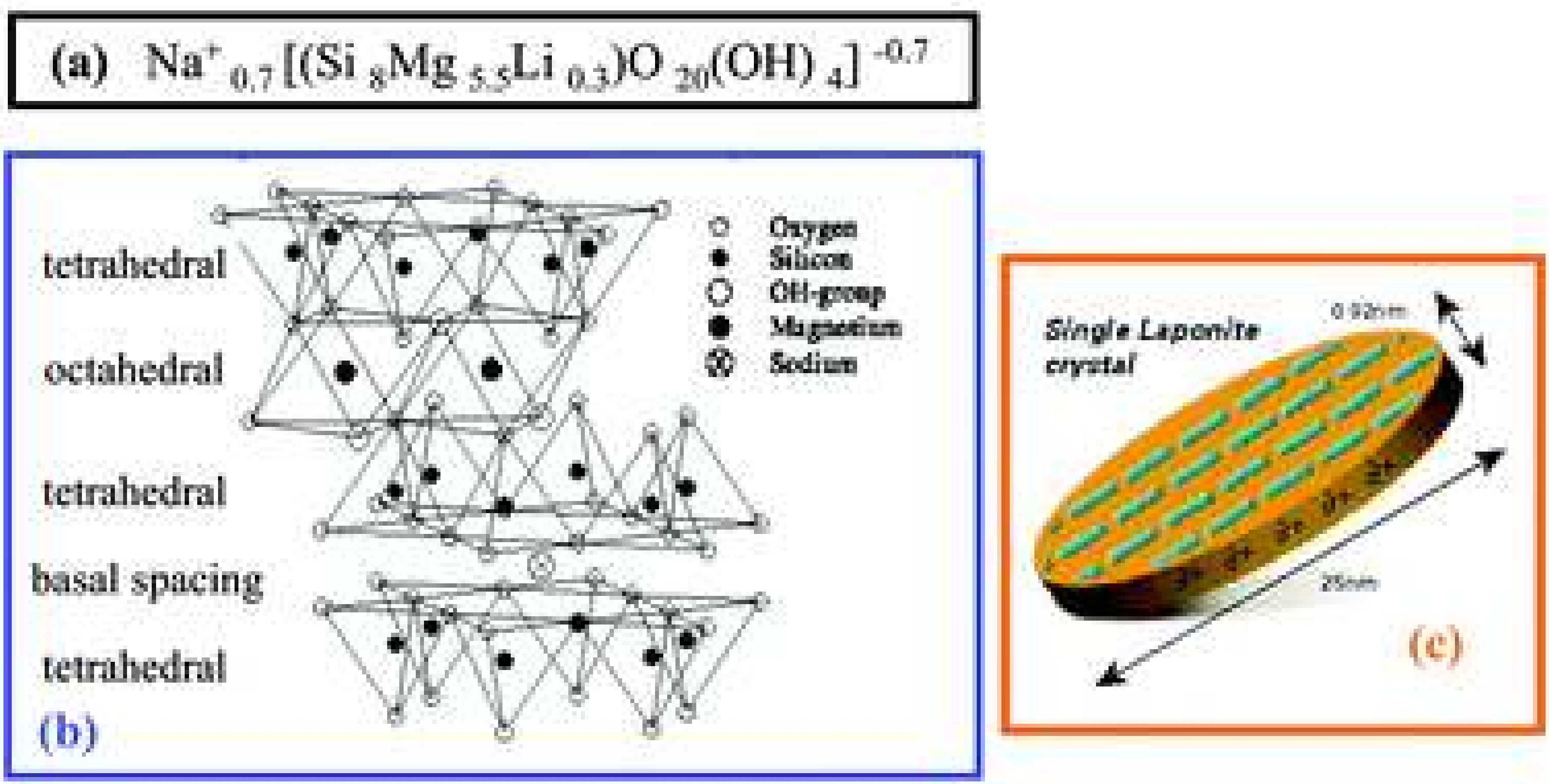
Isotropic Phase (O.P. = 0)

Nematic Phase (O.P. ≠ 0)

Irving Langmuir (Nobel Prize in Chemistry 1932): 1st experimental work in 1938 on liquid crystal structures in a clay suspension.

J. Chem Phys. 6, 873 (1938)

The most common and most used synthetic clay: Laponite



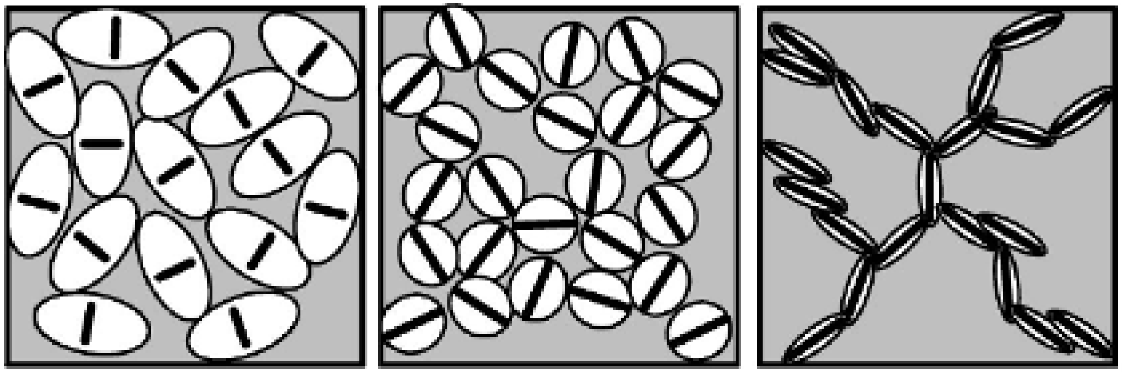
Colloidal gels: **Clay goes patchy**,
W. K. Kegel & H. N. W. Lekkerkerker,
Nature Materials 10, 5–6 (2011)

Observation of empty liquids and **equilibrium gels in a colloidal clay**,
B. Ruzicka, E. Zaccarelli, L. Zulian, R. Angelini, M. Sztucki, A. Moussaïd,
T. Narayanan and F. Sciortino, **Nature Materials 10, 56-60 (2011)**

PHYSICAL REVIEW E **69**, 031404 (2004)

Nonergodic states of charged colloidal suspensions: Repulsive and attractive glasses and gels

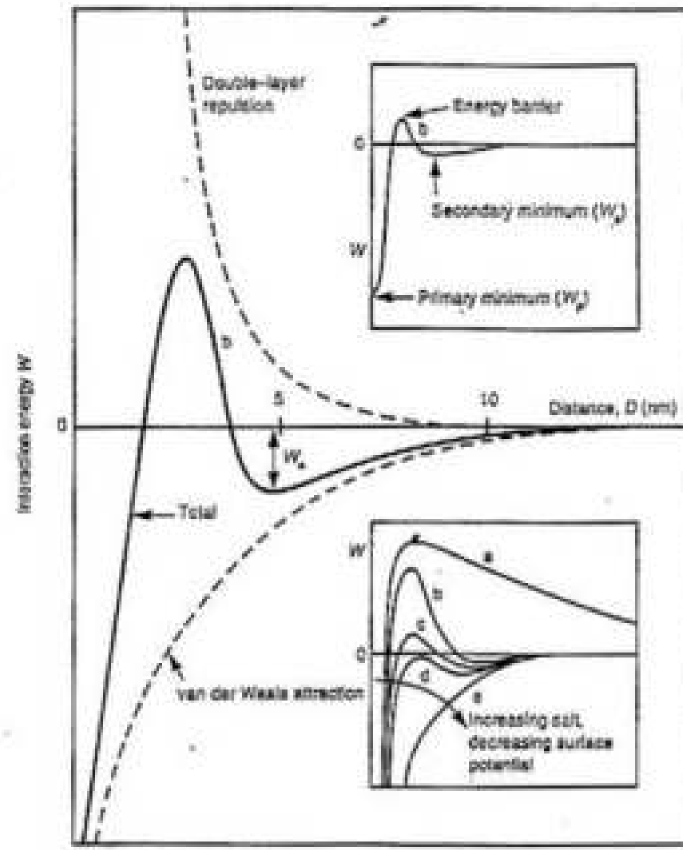
Hajime Tanaka,[1] Jacques Meunier,[2] and Daniel Bonn[2,3]



(a) (b) (c)

FIG. 1.
Schematic figures representing repulsive ''Wigner'' colloidal glass (a), attractive glass (b), and gel (c). Each thick line represents a Laponite disk, while a white ellipsoid represents the range of electrostatic repulsions: (a), long-range electrostatic repulsions dominate. (b), attractive interactions affect the spatial distribution but repulsive interactions still
play the predominant role in the slow dynamics of the system. (c), attractive interactions play a dominant role; a percolated network forms, which gives the system its elasticity and higher yield stress.

DLVO Theory: vdW + Screened Electrostatic Rep.

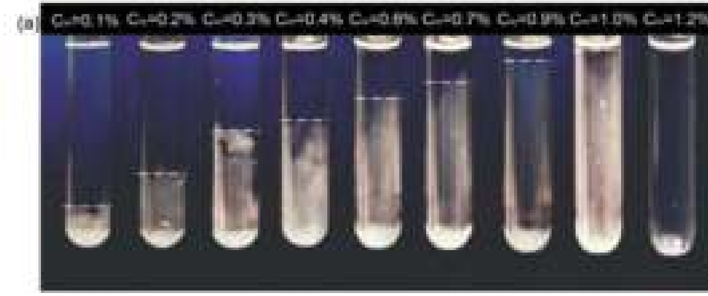


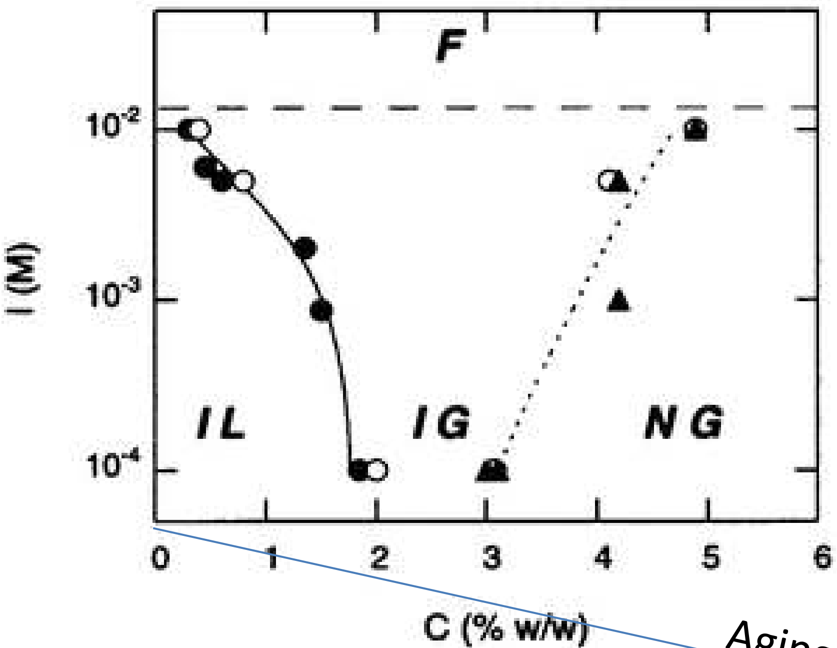
Langmuir **1998**, *14*, 4718–4723

On Viscoelastic, Birefringent, and Swelling Properties of Laponite Clay Suspensions: Revisited Phase Diagram

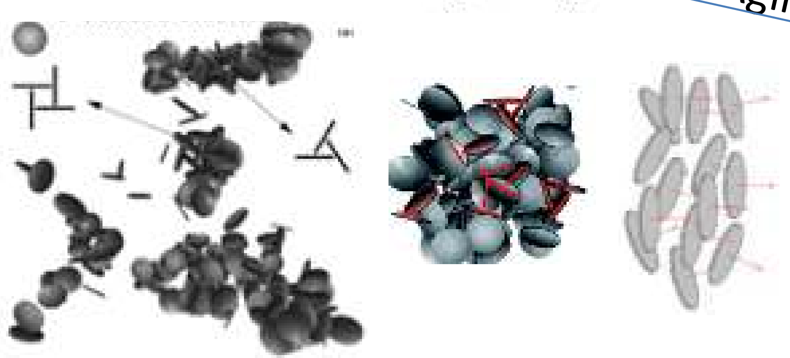
A. Mourchid,* E. Lécolier, H. Van Damme, and P. Levitz*

One sample for each point





Aging time



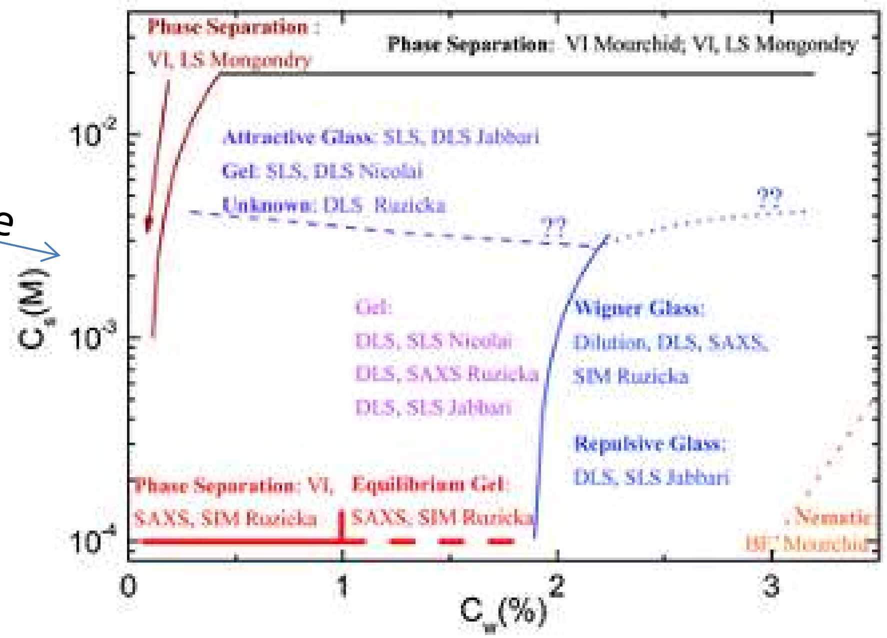
Soft Matter

Cite this: *Soft Matter*, 2011, **7**, 1268

www.rsc.org/softmatter

A fresh look at the Laponite phase diagram

Barbara Ruzicka and Emanuela Zaccarelli



Soft Matter

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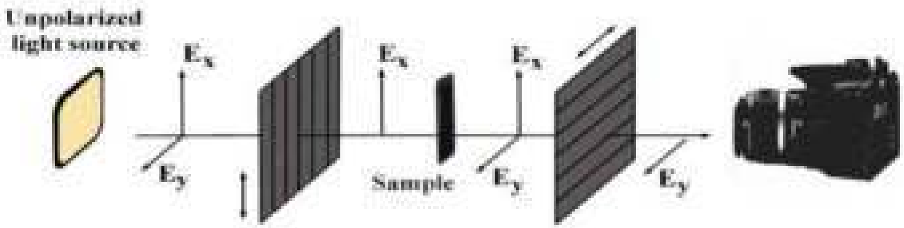
Orientational order in a glass of charged platelets with a concentration gradient

Cite this: Soft Matter, 2013, 9, 9999

Elisabeth Lindbo Hansen,[*a] Sara Jabbari-Farouji,[b] Henrik Mauroy,[c] Tomás S. Plivelic,[d] Daniel Bonn[e] and Jon Otto Fossum[a]



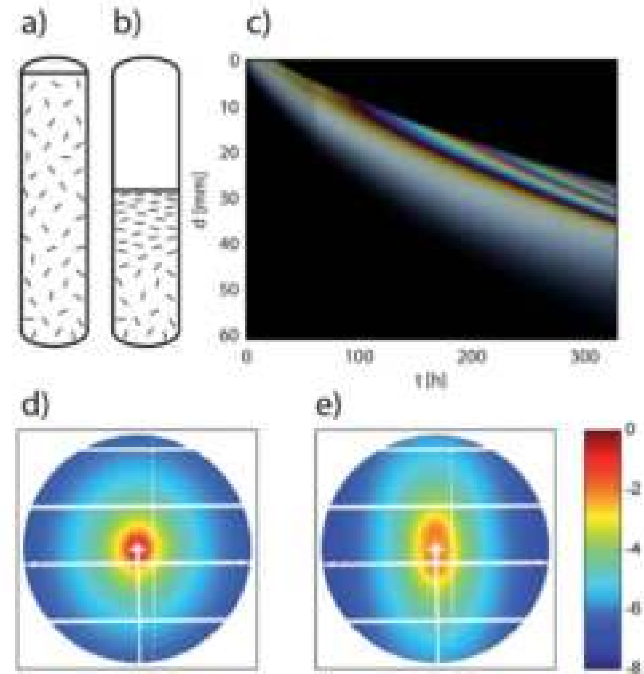
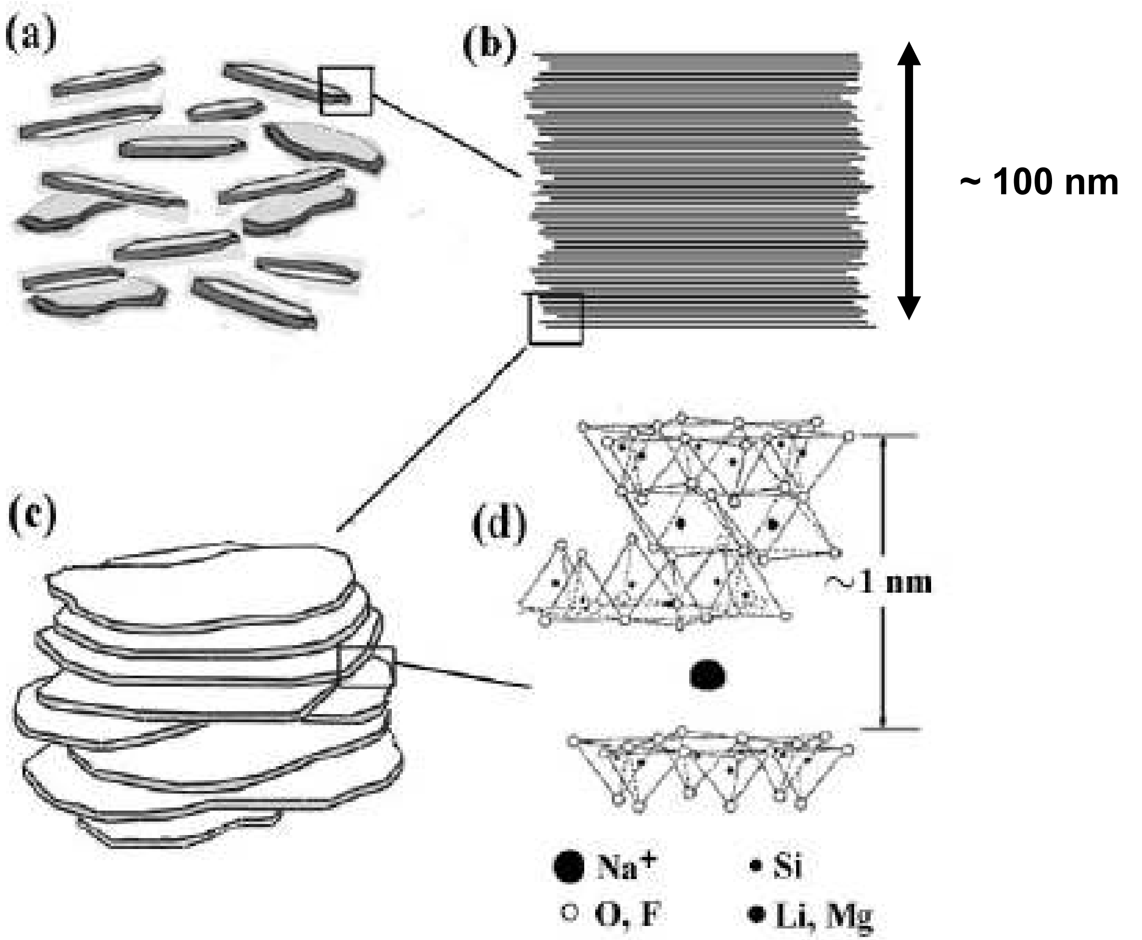


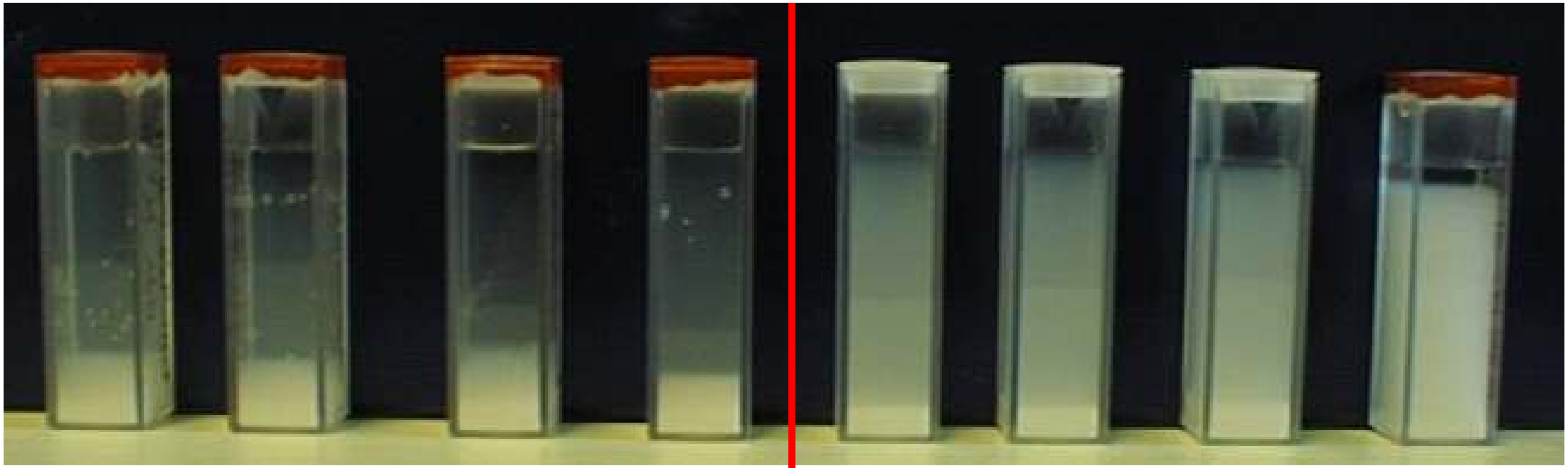
Fig. 2 a) Schematic of the structure of an isotropic Laponite glass and (b) of a Laponite glass with evaporation-induced orientational order. (c) A spatio-temporal plot of developing birefringence in an evaporating $C_w = 3.0$ wt% LRD sample, showing the central part of a capillary imaged at successive waiting times. Crossed linear polarizers were oriented at 45 deg with the vertical capillary axis. The thickness of the sample was $l = 2.65$ nm, so that 4th order magenta, appearing at the interface near the end of this time series, implies a $\Delta n = 8.3 \times 10^{-4}$. (d) SAXS pattern collected from the sample imaged in (c) at a distance of 10 mm from the interface, at the end of the time series, and (e) just below the interface.

Our clay experimental model system:

Q-fluorohectorite synthetic clay: Q_x-$(Mg_{3-x}Li_x)Si_4O_{10}F_2$,
Q is the exchangeable cation (Q = Na^+, Li^+, Ni^{2+}, Fe^{3+}, etc)



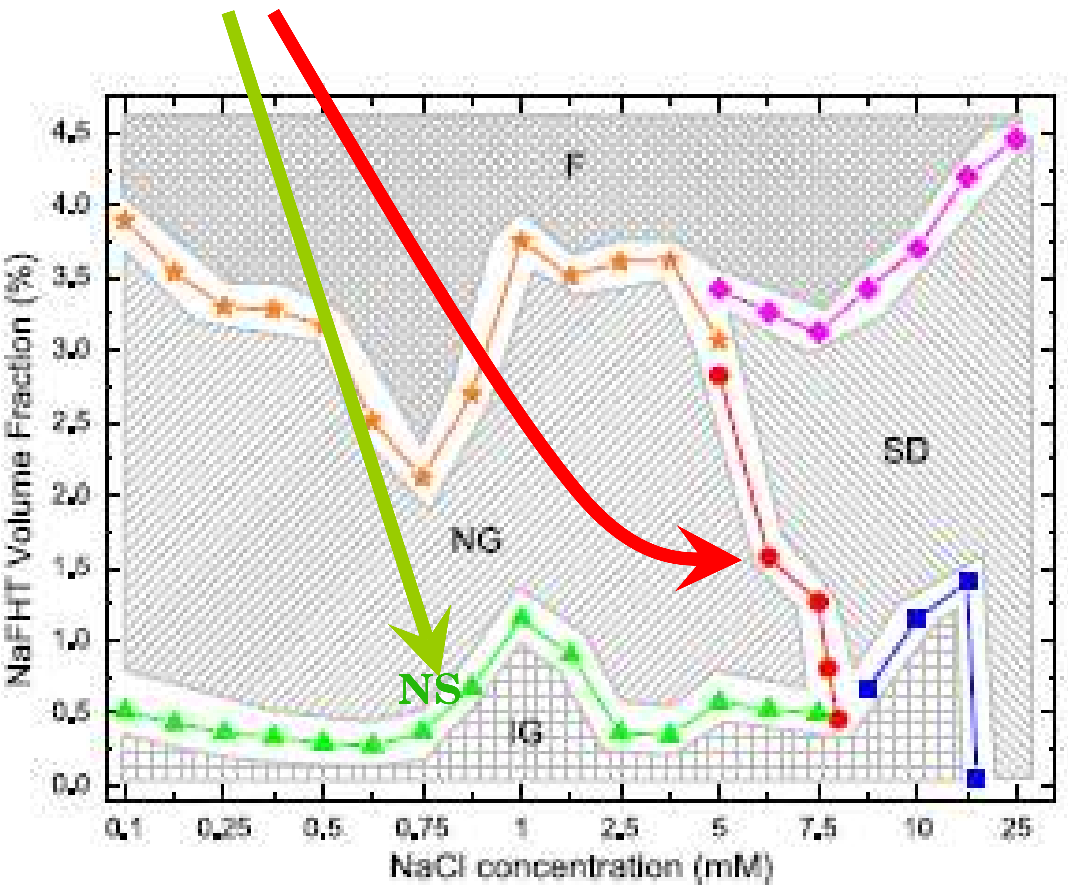
Increasing salt:



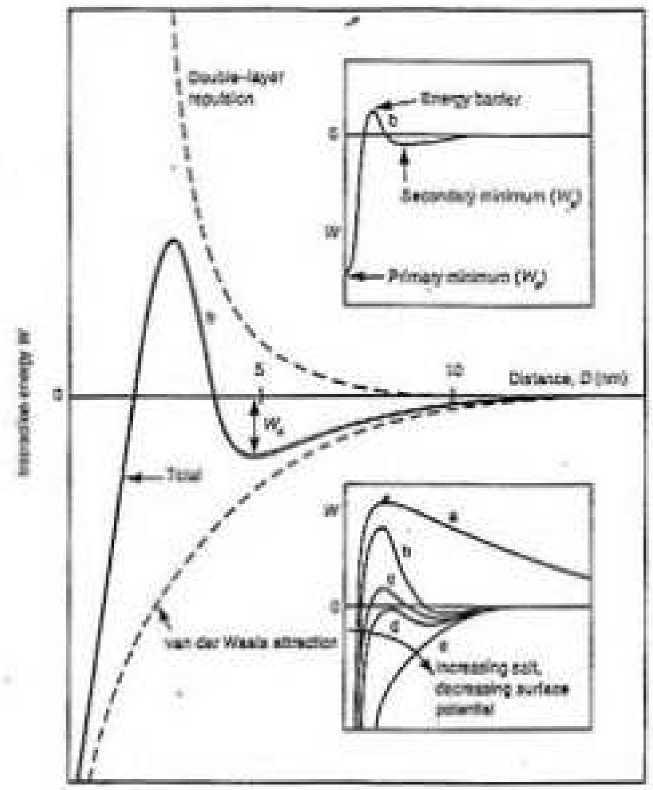
"Repulsive nematic" "Wigner glass"	"Attractive nematic" "Gel"
Particles push each other out towards container walls, → nematic at high enough concentration → «large» domains	Particles "catch each other" in DLVO local minima → «small» domains

The phase diagram of polydisperse Na-Fluorohectorite–water suspensions: A synchrotron SAXS study, D. M. Fonseca, Y. Meheust, J. O. Fossum, K. D. Knudsen, and K. P. S. Parmar,
Phys.Rev. E 79, 021402 (2009)

Transitions of interest



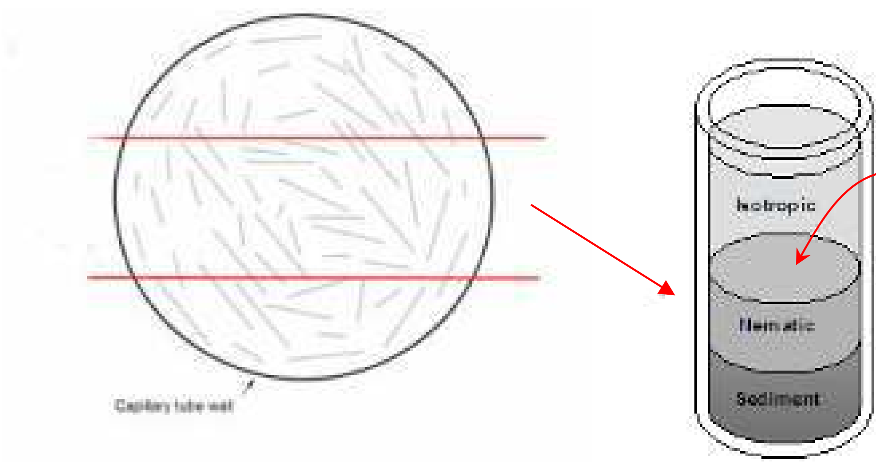
Obtained by combining:
- Eccentricity of SAXS scattering
- Angle of tilt of SAXS scattering
- X-ray transmission



Order Parameter = O.P.
= Angular distribution function
= $S_2 = ½\langle 3\cos^2\theta - 1\rangle$

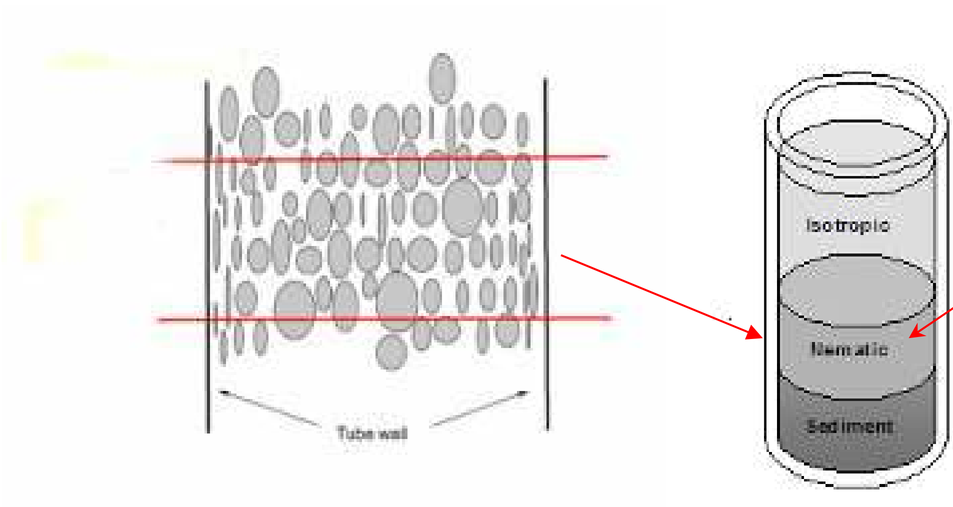
DLVO theory: vdW + Screened electrostatic rep.
(i.e The clay particles are effectively soft)

Cartoon of nematic phase of clay platelets seen from above:



Wall anchoring

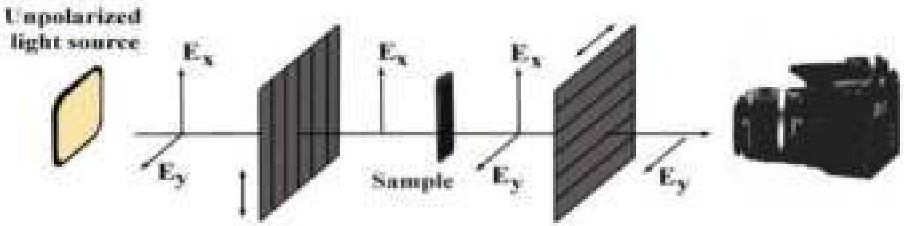
Cartoon of nematic phase of clay platelets, side-view:

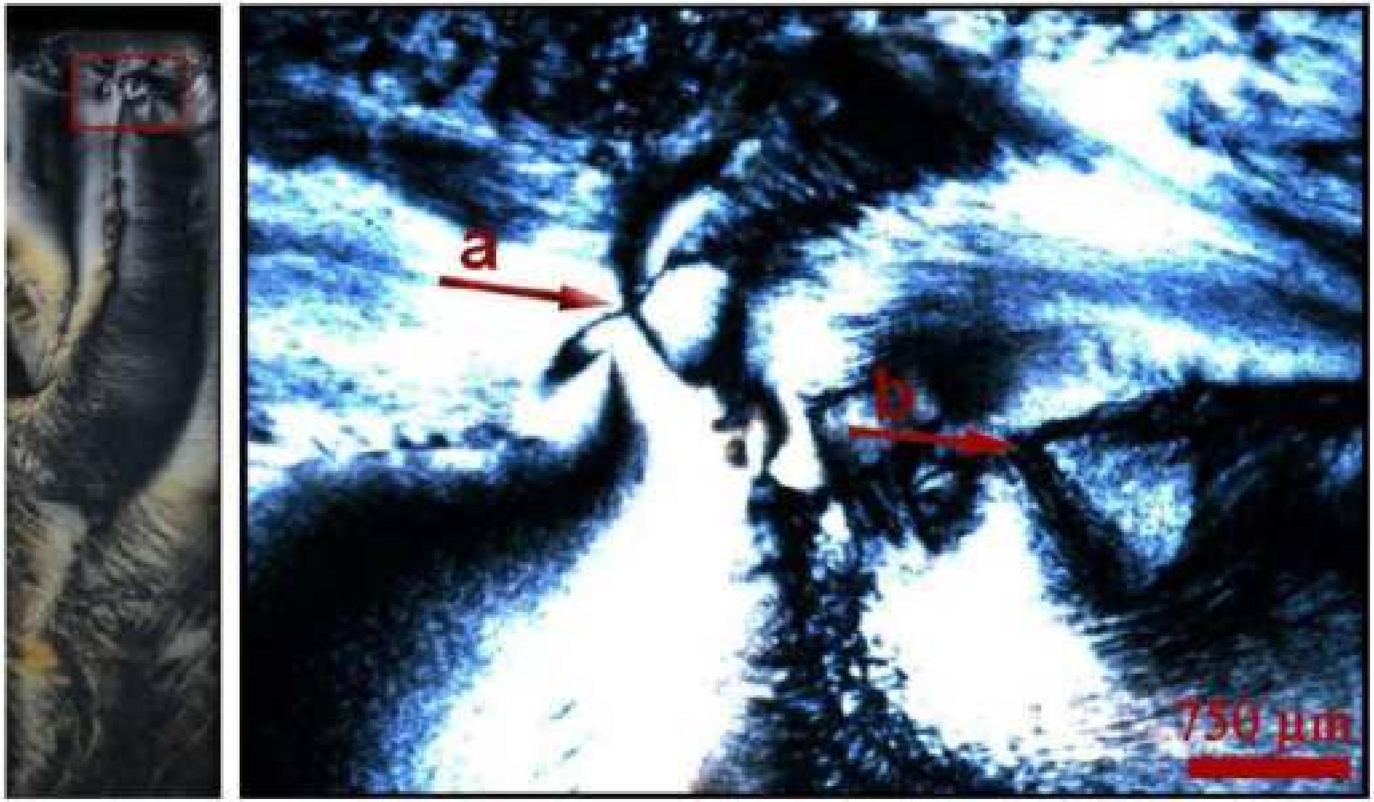


Order Parameter = O.P.

= Angular distribution function

$= S_2 = \frac{1}{2}\langle 3\cos^2\theta - 1\rangle$





a and **b**
are "typical" nematic defect signatures: Disclinations ("discontinuity" in the "inclination" of the director)

Nematic textures in colloidal dispersions of Na-fluorohectorite synthetic clay. N.I. Ringdal, D.M. Fonseca, E.L. Hansen, H. Hemmen, and J.O. Fossum. **Phys.Rev. E 81, 041702 (2010)**

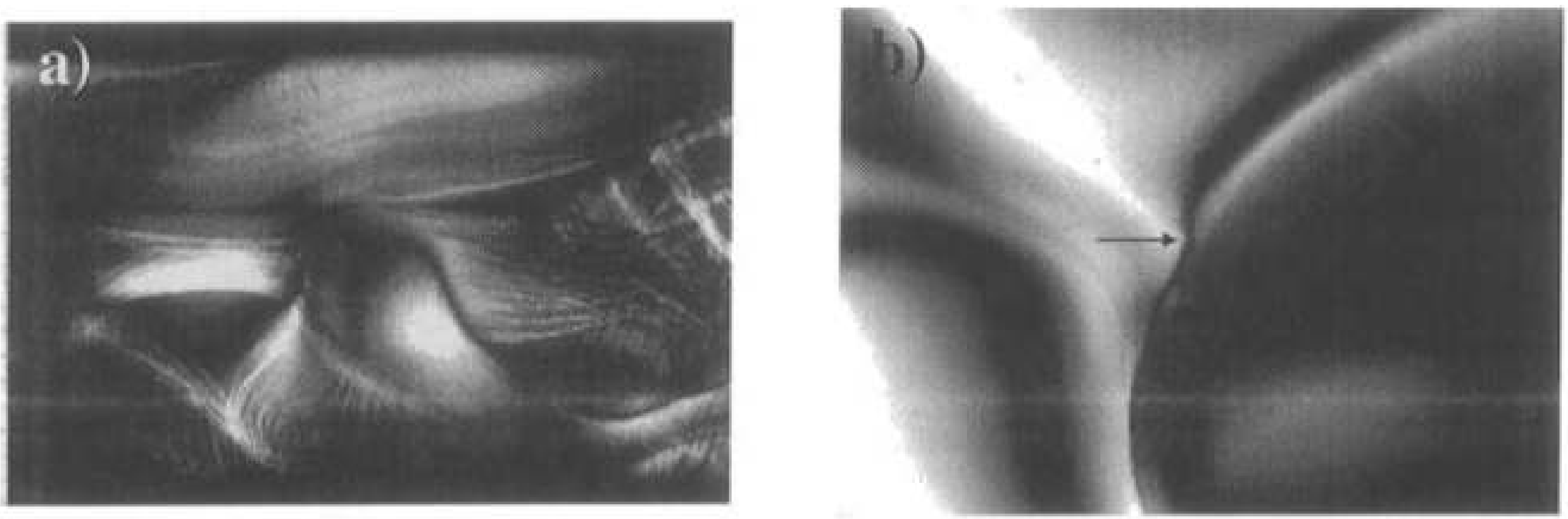
J. Phys. Chem. **1996,** *100,* 11139–11143

Observation of Nematic Liquid-Crystal Textures in Aqueous Gels of Smectite Clays

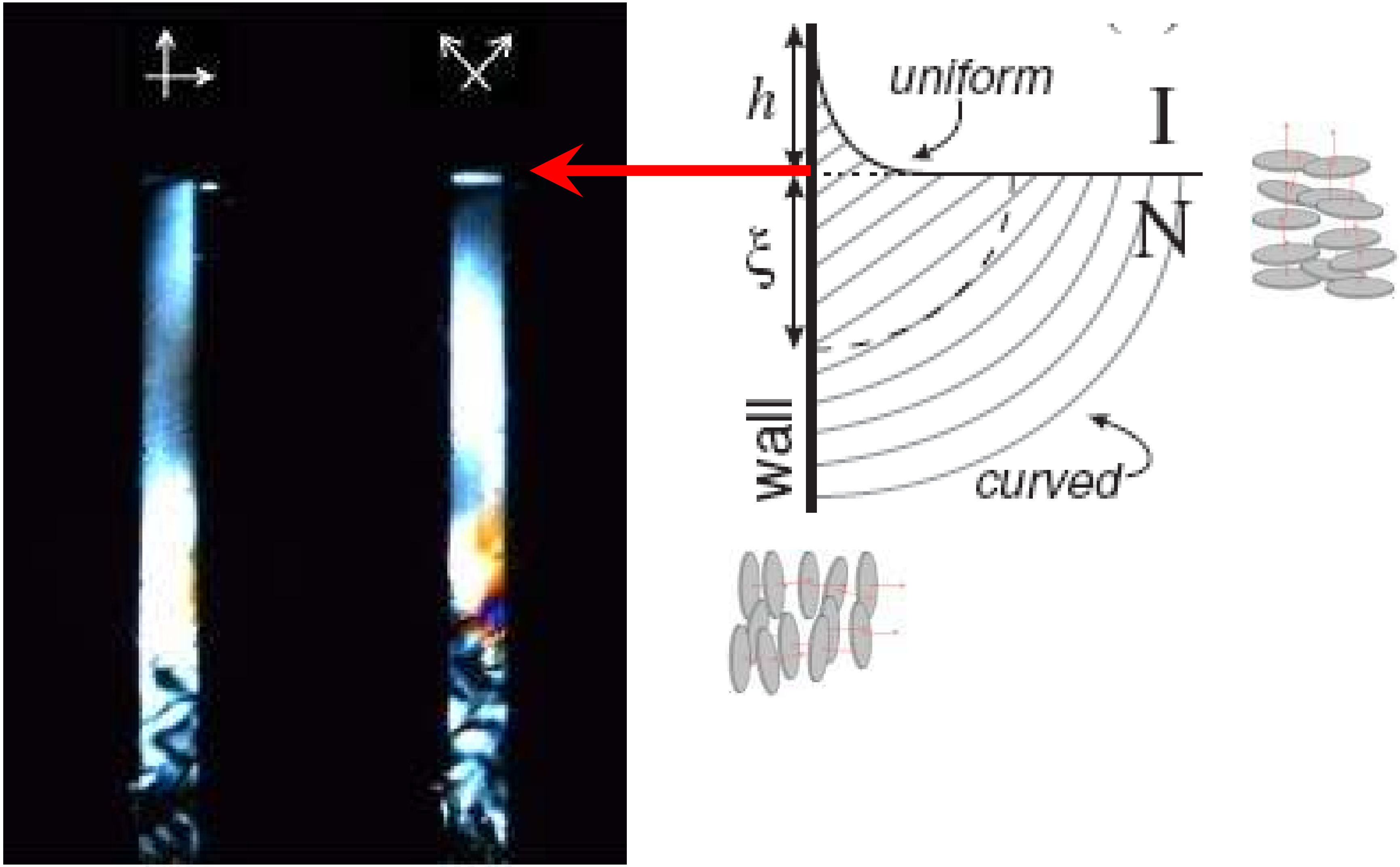
Jean-Christophe P. Gabriel,*,† Clément Sanchez,‡ and Patrick Davidson†,§

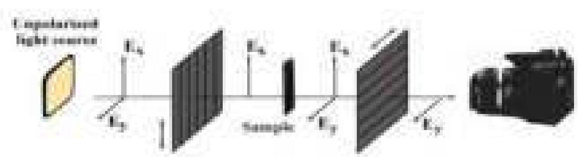
Materials Research Laboratory, University of California, Santa Barbara, California 93106, and Laboratoire de Chimie de la Matière Condensée (CNRS), Université Pierre et Marie Curie, 75252 Paris, France

Received: April 11, 1996®



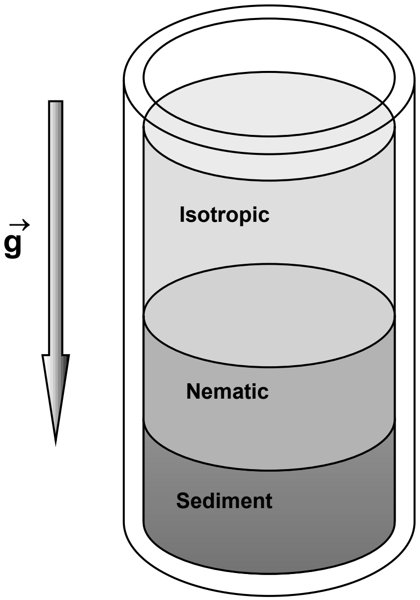
Anchoring to Nematic-Isotropic Interface:





The Isotropic-Nematic Interface in Suspensions of Na-Fluorohectorite Synthetic Clay. H. Hemmen, N. I. Ringdal, E. N. De Azevedo, M. Engelsberg, E. L. Hansen, Y. Meheust, J. O. Fossum and K. D. Knudsen. **Langmuir 25, 12507–12515 (2009)**

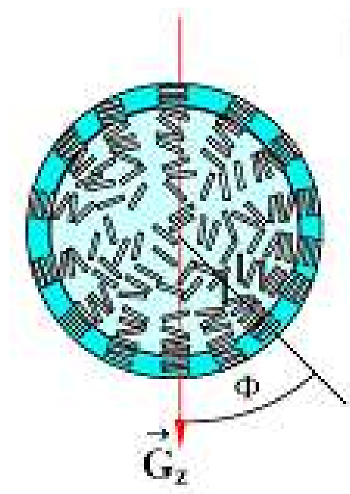
Response to magnetic field: Magnetic field guided self-organization:



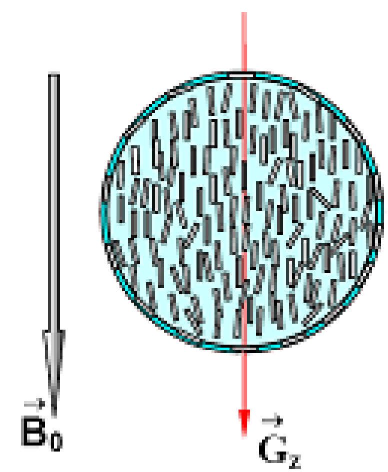
Glass wall anchoring confirmed by spatially resolved MRI measurements of anisotropic self-diffusion coefficient of water in the nematic phase.

Magnetic field induced ordering, due to diamagnetic anisotropy of the platelets at fields <u>above about 1 Tesla</u>.

$S_2 \sim -0.3$

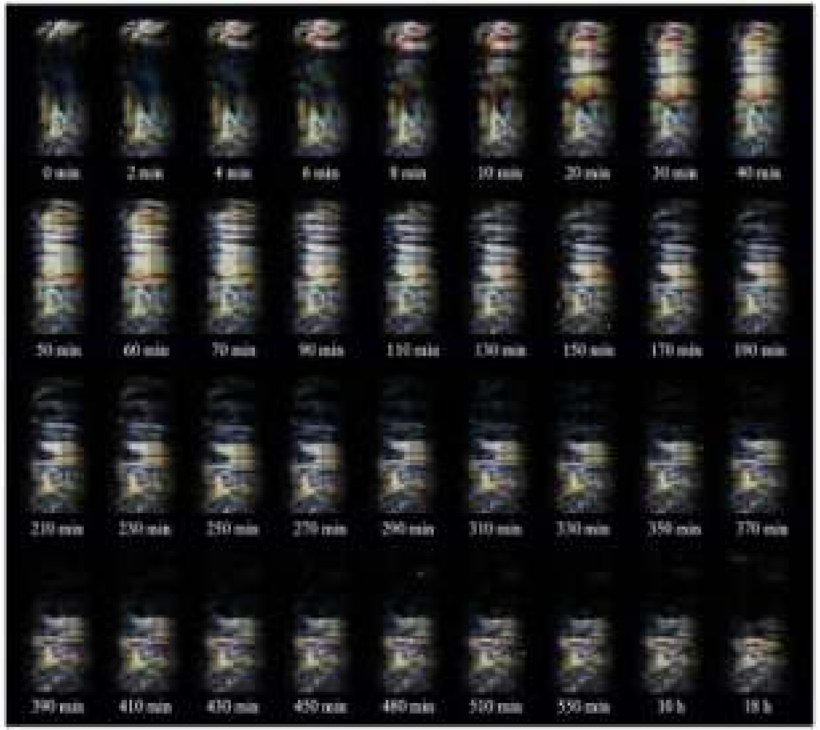


$S_2 \sim +0,5$

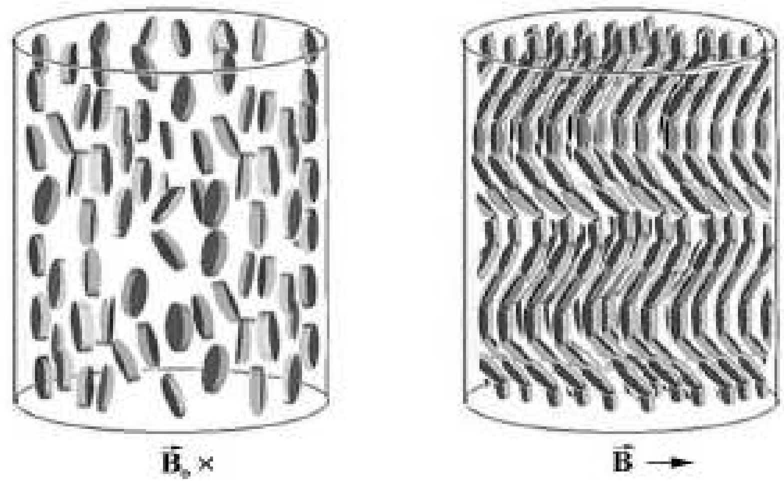


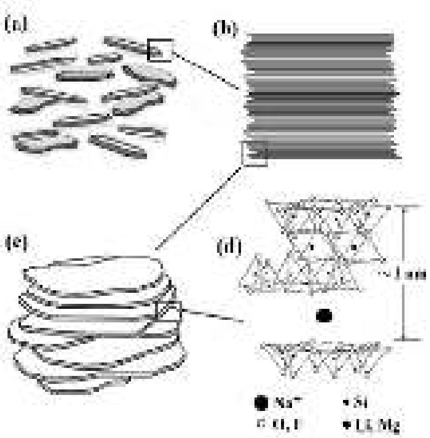
Anisotropic water diffusion in nematic self assemblies of clay nano-platelets suspended in water. E. N. de Azevedo, M. Engelsberg, J. O. Fossum and R. E. de Souza, **Langmuir 23, 5100 (2007)**

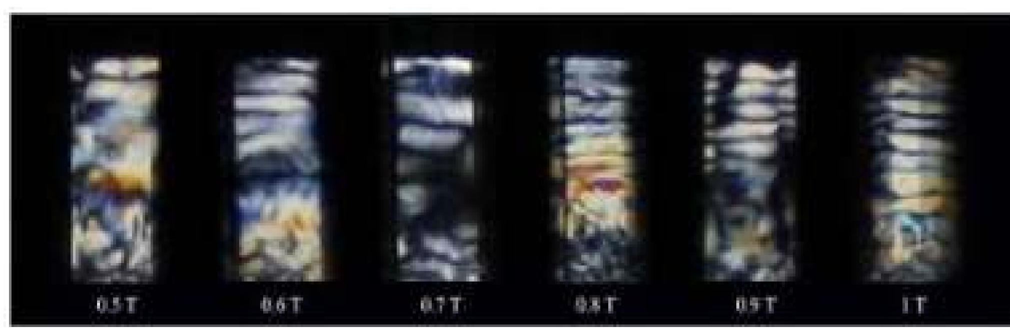
Color control of clay nematics between crossed polarizers



The Frederiks transition in an aqueous clay dispersion, H. Hemmen, E.L. Hansen, N.I. Ringdal and J.O. Fossum,
Revista Cubana de Fisica, vol. 29-1E, 59-61 (2012)

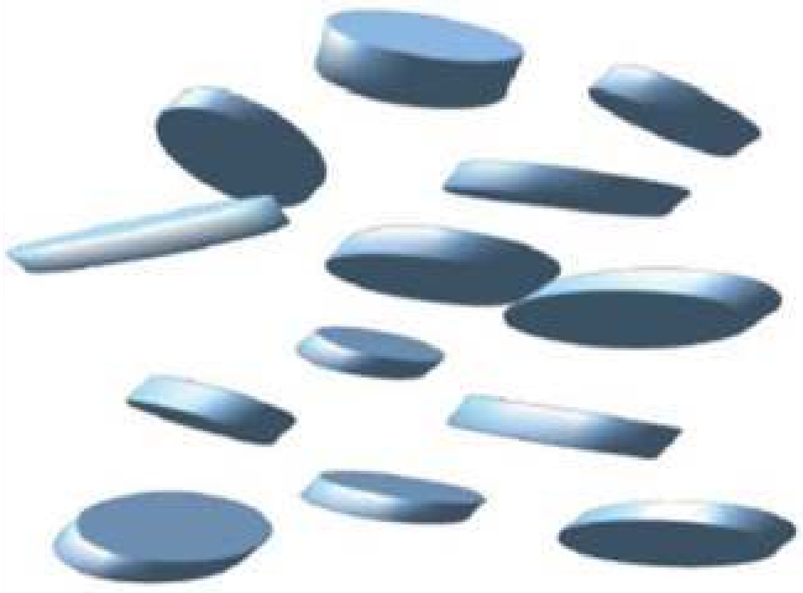






Self-assembly:

Making a macroscopic sample (i.e. about 10^{20} nanoparticles) by physically picking up and moving nanoparticles into place, one by one, would take about 300 million years, even if the time for moving individual particles could be made as short as 1 millisecond.



NTNU

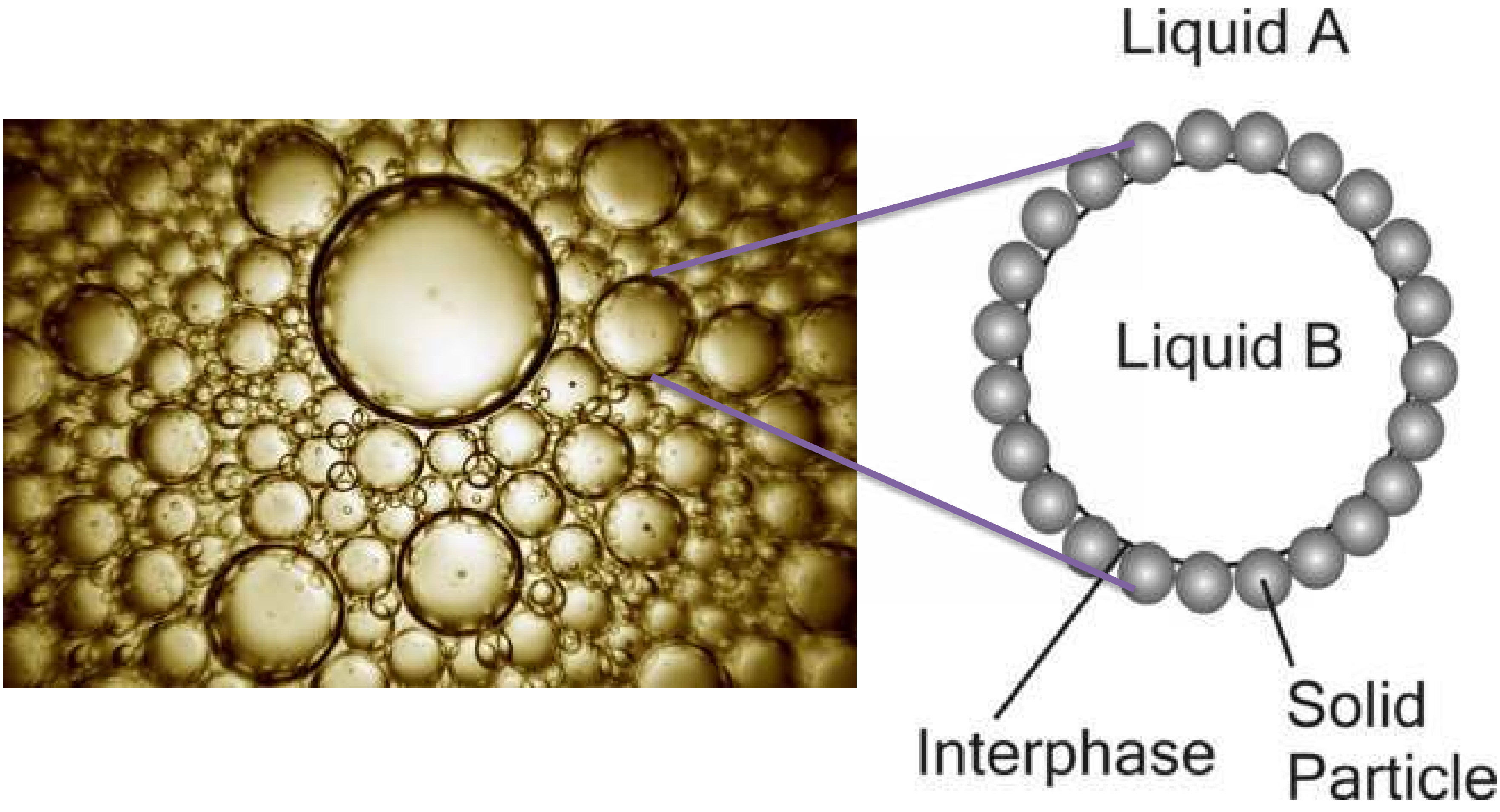
Human made design:
Top-down Self-assembly

How nature works:
Bottom-up Self-assembly

Scientific challenge of nanostructured self-assembly:
Combination of Top-down and Bottom-up:

Another pile of rocks

Clay particles as emulsion stabilizers: Pickering («physical») emulsions



"Separation of Solids in the Surface-layers of Solutions and 'Suspensions' (Observations on Surface-membranes, Bubbles, Emulsions, and Mechanical Coagulation).—Preliminary Account." By W. RAMSDEN, M.A., M.D., Oxon., Fellow of Pembroke College, Oxford. Communicated by Professor F. GOTCH, F.R.S. Received June 8,—Read June 18, 1903.

J. Chem. Soc., Trans., 1907,**91**, 2001-2021

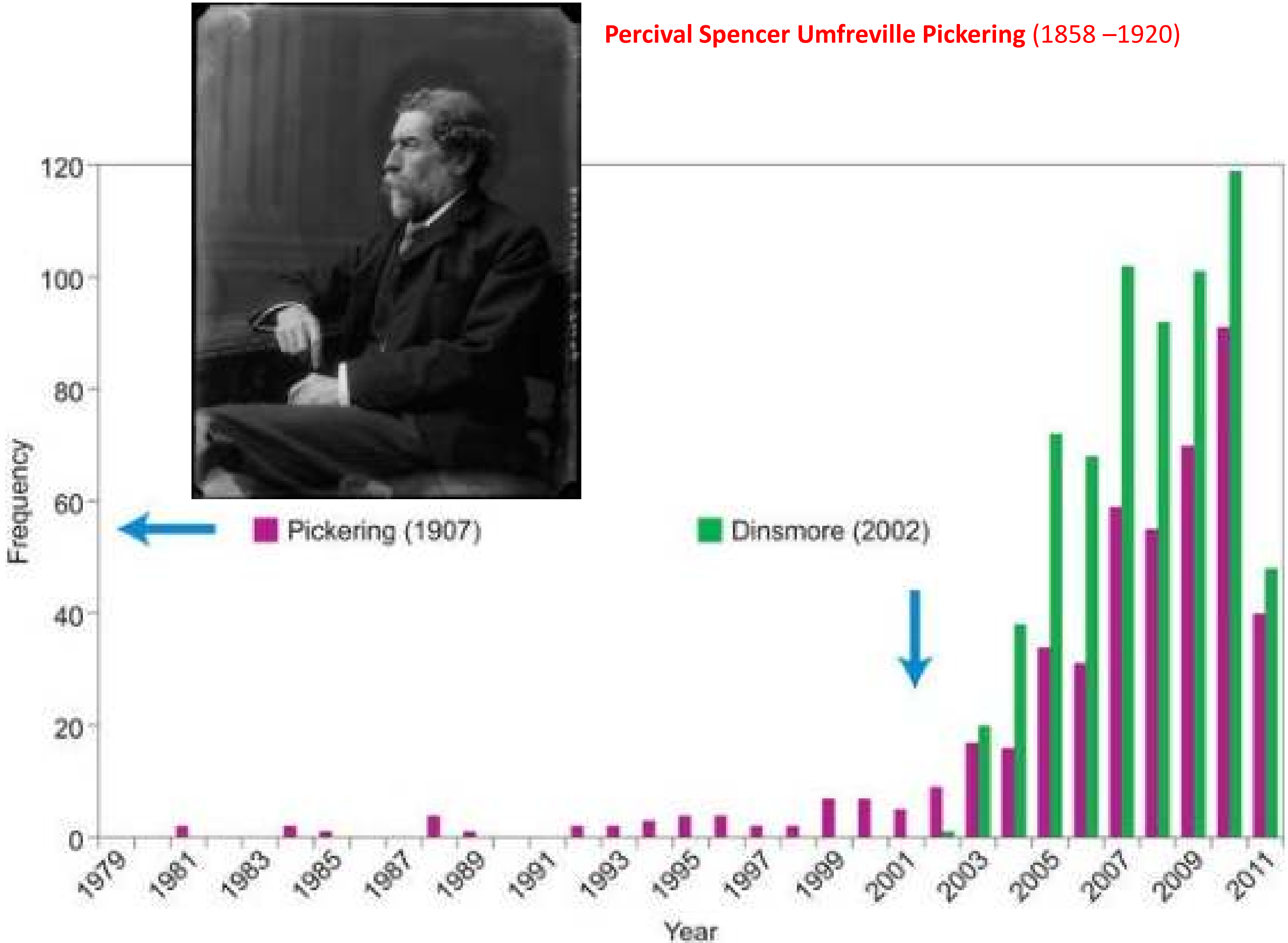
CXCVI.—*Emulsions.*

By SPENCER UMFREVILLE PICKERING, M.A., F.R.S.

IN the Sixth Report of the Woburn Experimental Fruit Farm (Eyre and Spottiswoode, 1906) were published the results of an examination of emulsions of paraffin oil in solutions of soft soap, such as are used for insecticidal purposes; this examination has now been extended with the double object of obtaining an emulsifying agent which would, for practical purposes, not be open to the objections presented by those containing soap, and also of elucidating the nature of emulsification. The subject had already been investigated by Ramsden (*Proc. Roy. Soc.*, 1903, **72**, 156), but his work, unfortunately, did not come under the notice of the writer until that here described had been completed. It is satisfactory to find, however, that Ramsden, pursuing a different line of enquiry, should have arrived at an explanation of emulsification which is essentially the same as that given here.

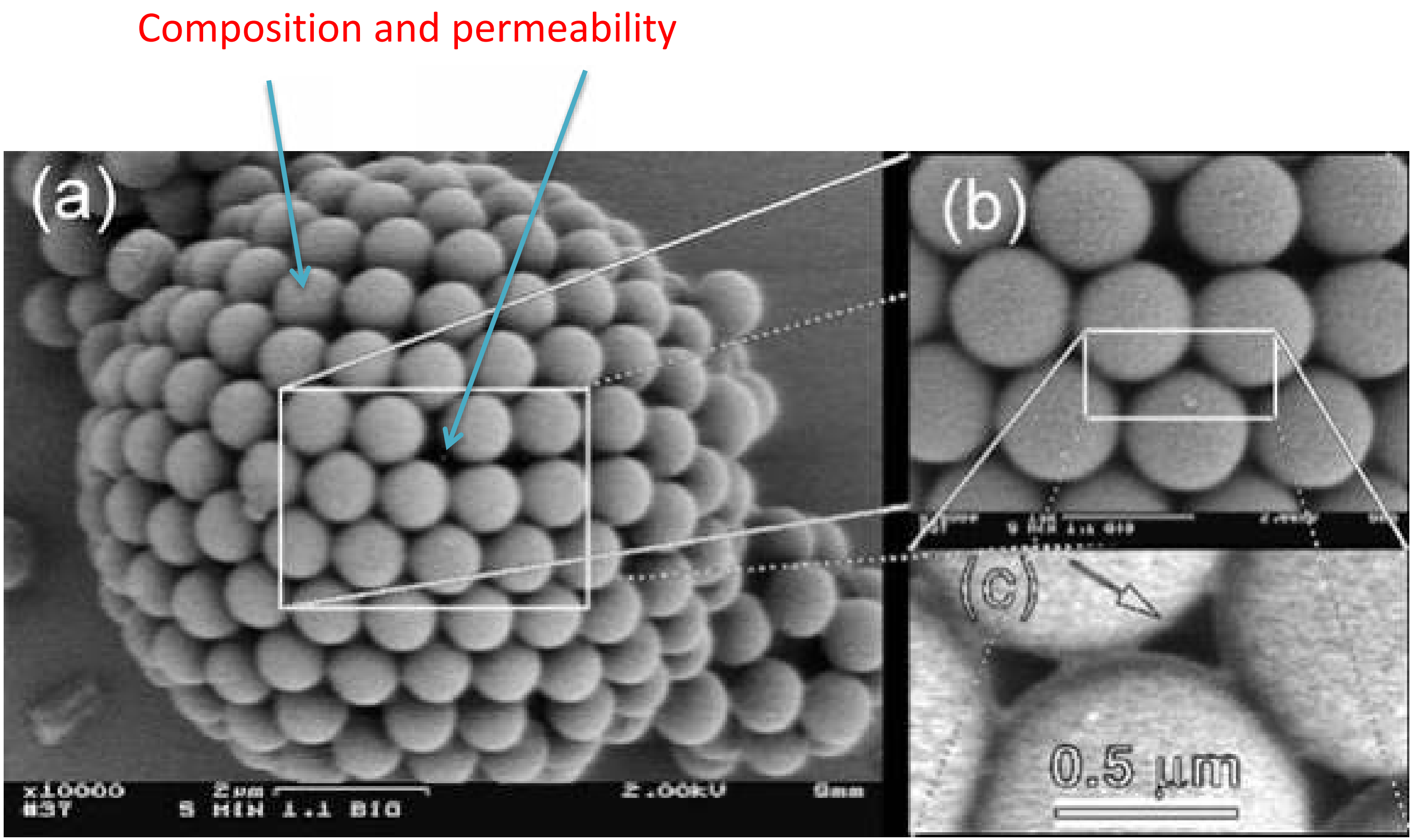
Percival Spencer Umfreville Pickering (1858 –1920)

Percival Spencer Umfreville Pickering (1858 –1920)



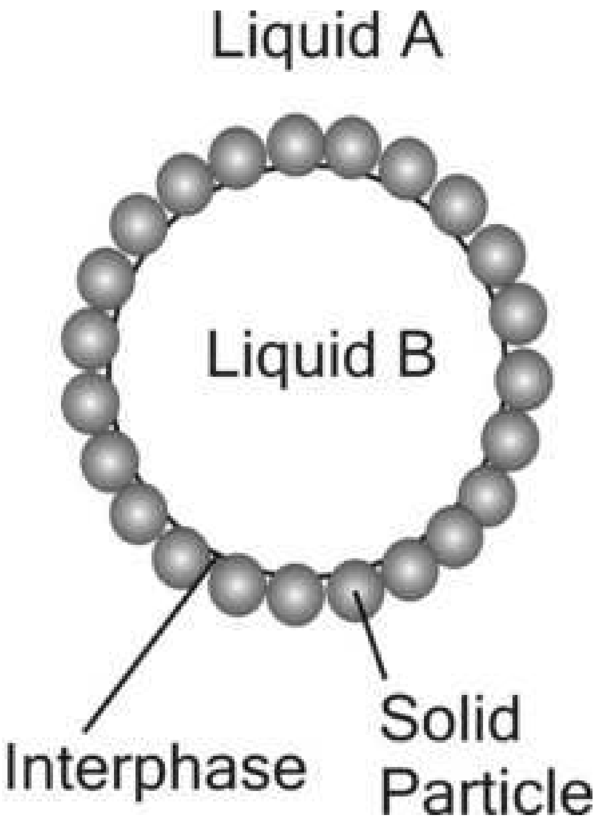
Lost history versus good science, Qian Wang, & Chris Toumey, Nature Chemistry 3, 832–833, doi:10.1038/nchem.1179 (2011)

Colloidosomes



A.D. Dinsmore et. Al., Science, **298**, 1006 (2002); David Weitz group: Harvard Univ.

Capillary binding



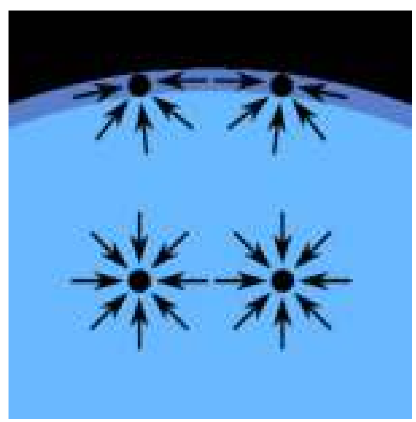
Surface Energy: $E = \gamma A$

$A = \text{Surface area} \quad \gamma_{WA} = 0.0073\,\text{N/m}$

Capillary binding: A particle at the interface is trapped in a capillary barrier with a substantial energy cost of moving to either side of the liquid interface.

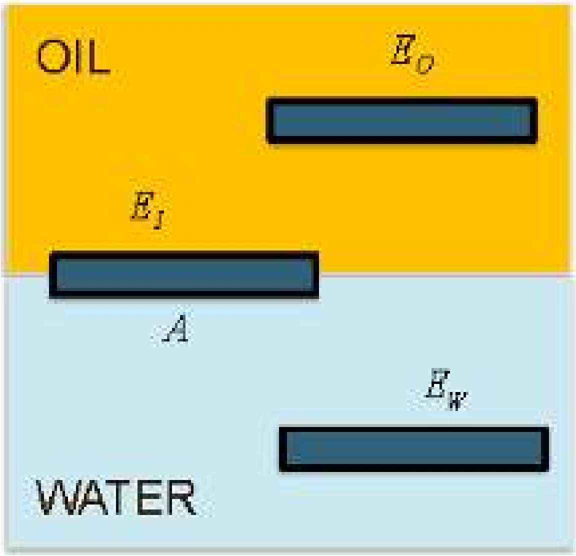
Origin of capillary binding:
Surface tension:

The forces on molecules of a liquid:



Surface tension preventing a paper clip from submerging

Capillary binding of a flat solid particle at a liquid interface



Particle surface energy :

$$E_O = 2A\gamma_{SO}$$

$$E_W = 2A\gamma_{SW}$$

$$E_I = A\gamma_{SO} + A\gamma_{SW} - A\gamma_{OW}$$

Energy gain :

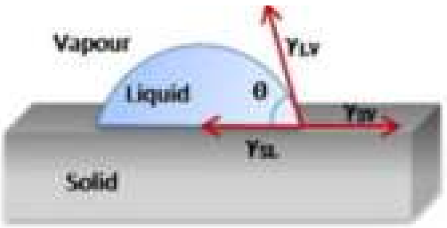
$$E_I - E_O = -A\gamma_{OW}(1+\cos\theta)$$

$$E_I - E_W = -A\gamma_{OW}(1-\cos\theta)$$

Wetting angle Young's relation:

$$\gamma_{SO} = \gamma_{SW} + \gamma_{OW}\cos\theta$$

Energetically favorable to adsorb particles at the interface.



Typically:

$A_p\gamma_{OW}$ ~ 10000 kT for microparticles

Oil drops in saline water with suspended Laponite clay particles: Pickering emulsion

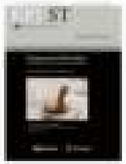
Article | OPEN

Transition from glass- to gel-like states in clay at a liquid interface

A. Gholamipour-Shirazi, M. S. Carvalho, M. F. G. Huila, K. Araki, P. Dommersnes & J. O. Fossum

Scientific Reports **6**, Article number: 37239 (2016)
doi:10.1038/srep37239

Received: 01 April 2016
Accepted: 18 October 2016
Published online: 24 November 2016



The European Physical Journal Special Topics
July 2016, Volume 225, Issue 4, pp 757–765

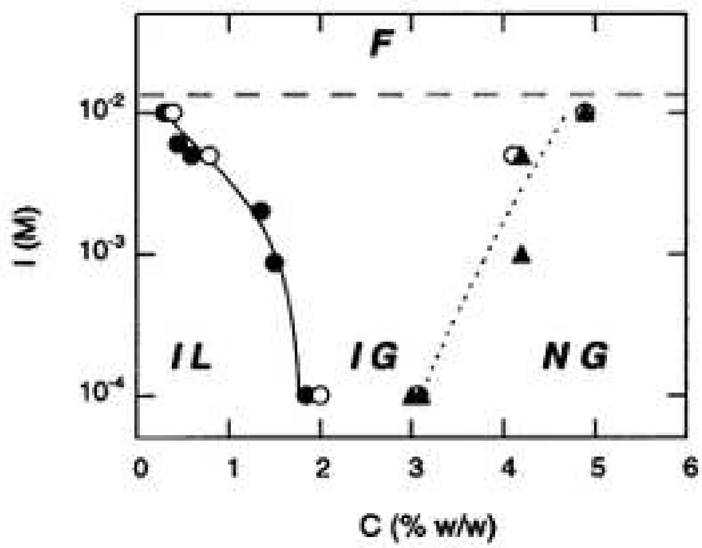
Controlled microfluidic emulsification of oil in a clay nanofluid: Role of salt for Pickering stabilization

Authors   Authors and affiliations

A. Gholamipour-Shirazi, M.S. Carvalho, J.O. Fossum

No salt:
Pickering film not observable by Raman microscopy.
Observable surface tension.

With salt:
~ 4 μm Pickering film.
Increased surface tension.



Until now in this talk:

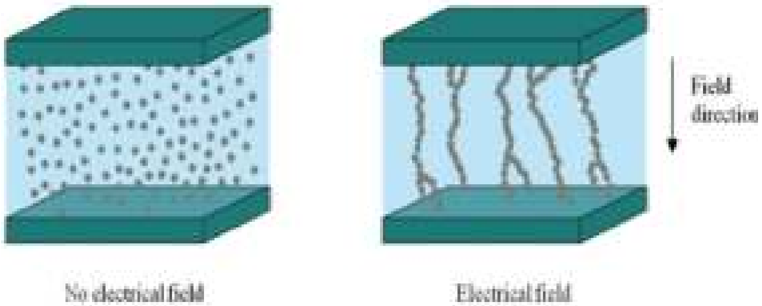
Self-assembly of clay particles suspended in saline water

(+ in one case with oil drops)

What about clay particles suspended in oil?

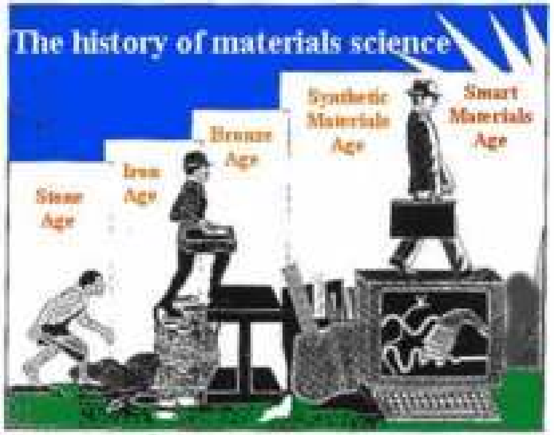
Electro-rheological fluids

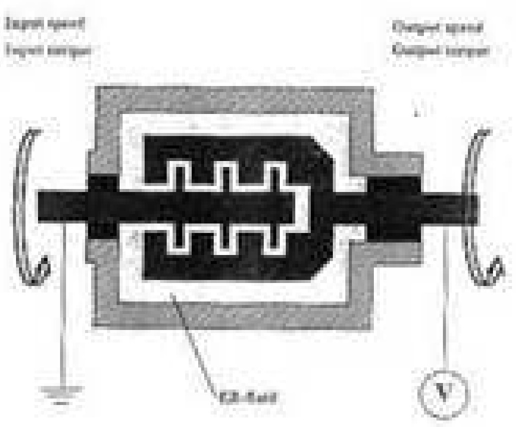
Winslow effect:

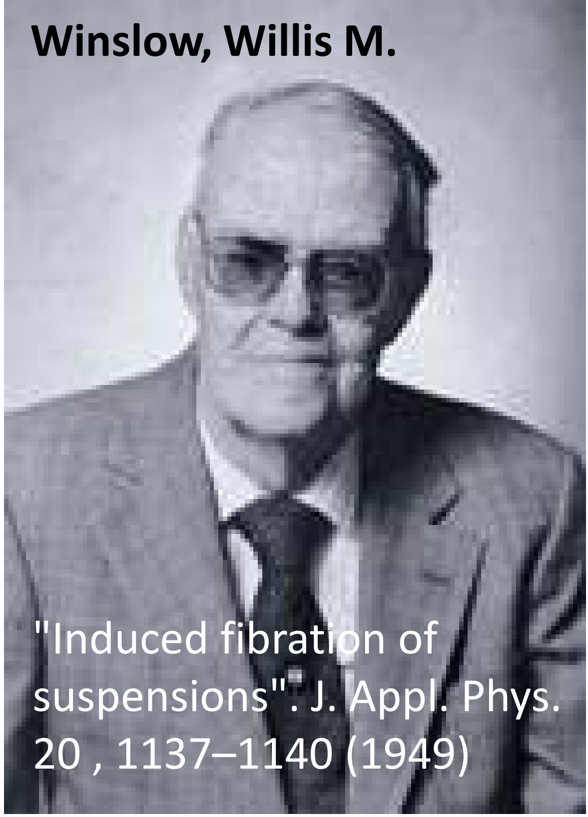


Viscosity can increase by a factor 100 000 in response to an electric field!

- Electric fields induce dipole attraction and chain formation
- Large yield stress -> 200 kPa or more 100 times viscosity increase (up to 100000 times according to wiki)

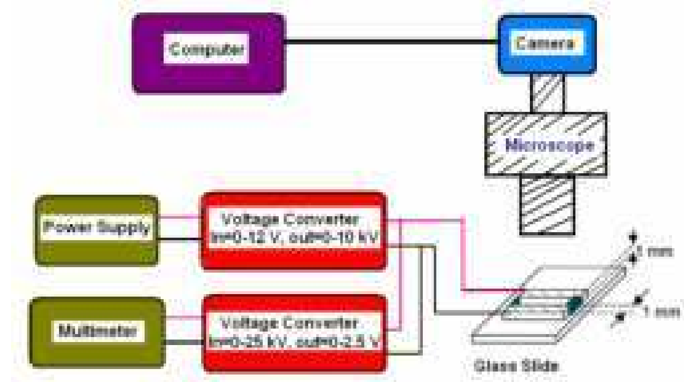




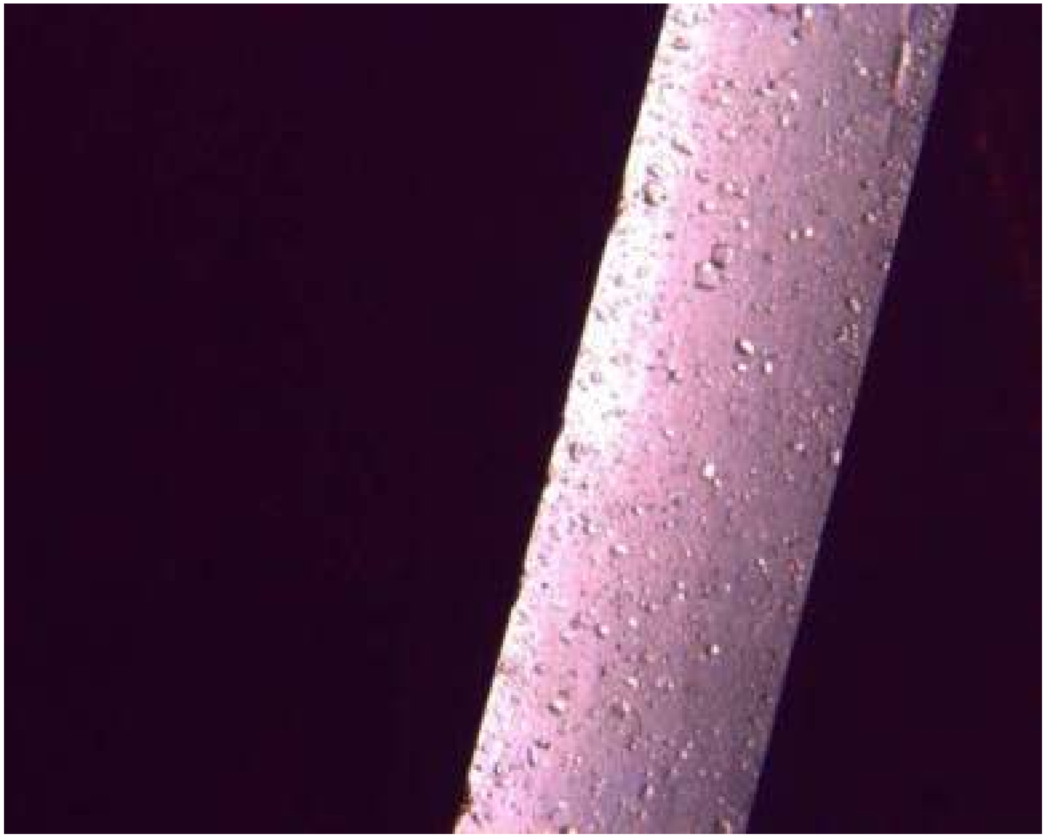


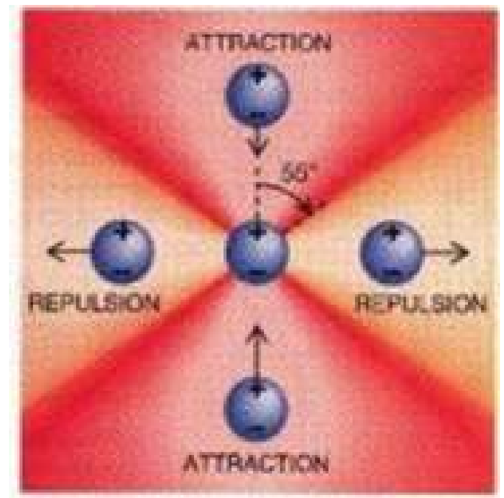
U.S. Patent 2,417,850: Winslow, W. M.: 'Method and means for translating electrical impulses into mechanical force', 25 March 1947

Clay particles suspended in oil:



Video microscopy (real time):

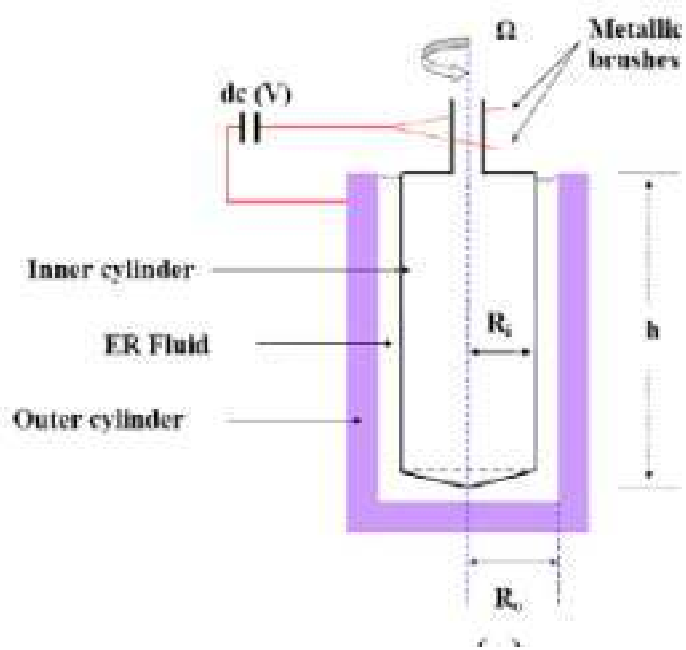




Electrorheology: Smart Materials

Intercalation-enhanced electric polarization and chain formation of nano-layered particles, J.O. Fossum, Y. Méheust, K.P.S. Parmar, K.D. Knudsen, K.J. Måløy and D. M. de Fonseca, Europhys. Lett., 74, 438-444 (2006)

Our Physica MCR 300 Rheometer inl electrorheol. cell:



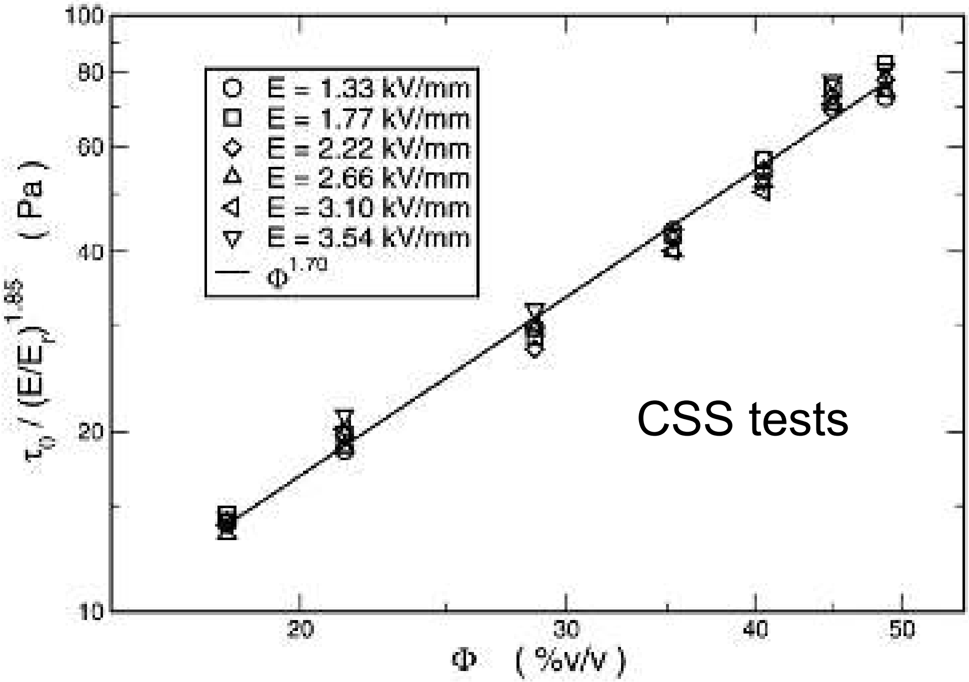
Langmuir 24, 1814 (2008)

J. Phys.: Condens. Matter 22, 324104 (2010)

J. Rheol. 55, 2011 (2010)

Yield stress:

Theories predict: $$\tau \propto E^{\alpha}\,\Phi^{\beta}$$



Static yield stress:
Yield stress for an undisrupted ER fluid.

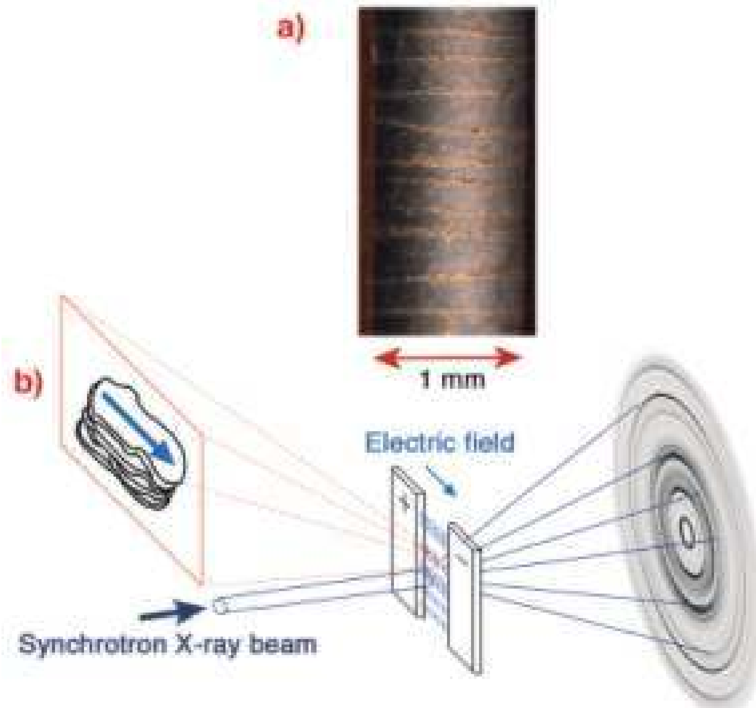
Log-log plot of the static yield stress, normalized by $E^{1.86}$, vs. the volume fraction at different strengths of the applied electric field. A power law $\beta \approx 1.70$ fits to the whole dataset..

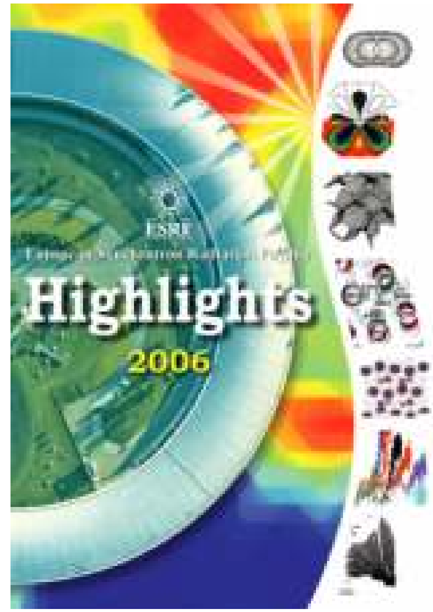
ER Suspensions of Laponite in Oil *Langmuir, Vol. 24, No. 5, 2008* 1821

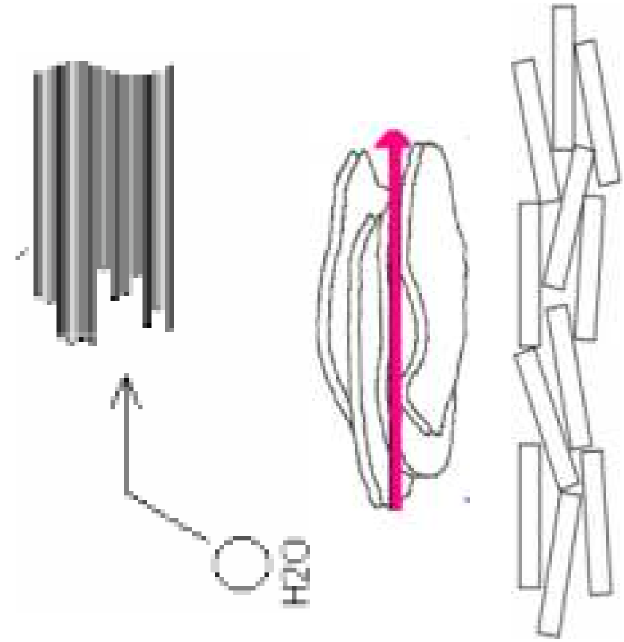
Table 1. Comparison of Static Yield Stress Values for Various ER Fluids Including That Addressed in the Present Paper, under an Applied Electric Field of About 1.0 kV/mm

ER fluids →	our sample	mica[18]	hematite[43]	saponite[44]	zeolite[45]	GER[46]
Φ →	1.9% (v/v)	15% (v/v)	15% (v/v)	0.11 g/mL	30% (v/v)	30% (v/v)
τ_0 (Pa) →	~20	~100	~85	~50	~3000	~15000

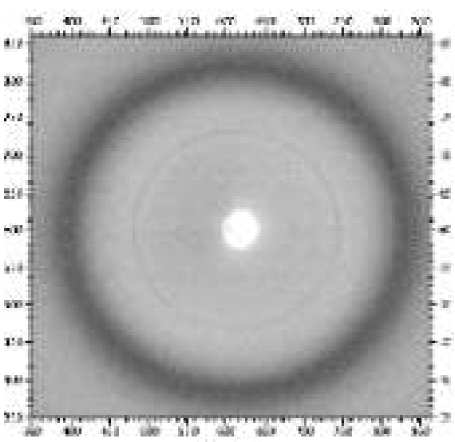
Experiments at ESRF, Grenoble:
In ESRF Scientific Highlights 2006



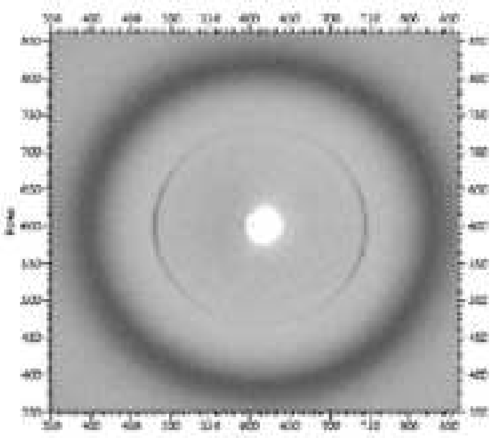


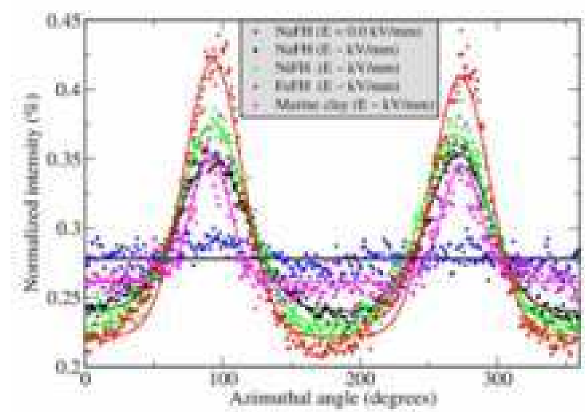


Before: 0 V/mm



After: 500 V/mm





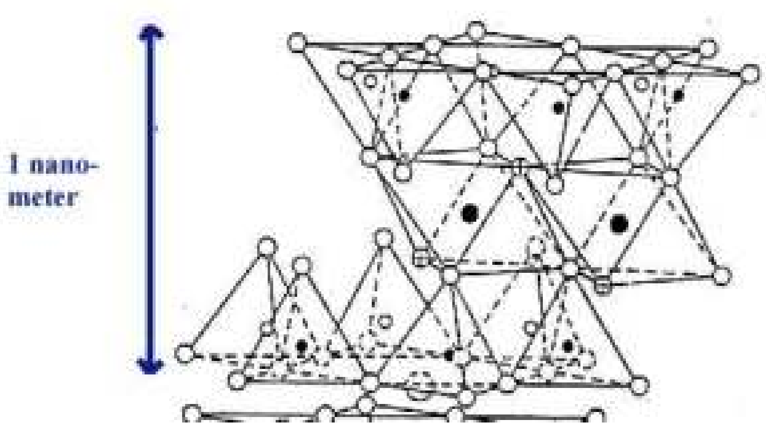
Angular distribution function
$= S_2 = ½<3\cos^2\theta-1>$

CLAY MINERALS AND THE ORIGIN OF LIFE

The confinement by cell membranes offers localized concentration and protection for biomolecules such as nucleic acids, leading to efficient biochemical reactions.

In defining the pre-cellular environment, it is important to address the following questions:

1) **How did biomolecules encounter each other and maintain sufficient proximity to perform complicated biochemical reactions?**
2) **How did the biomolecules survive in the environment without any protection?**

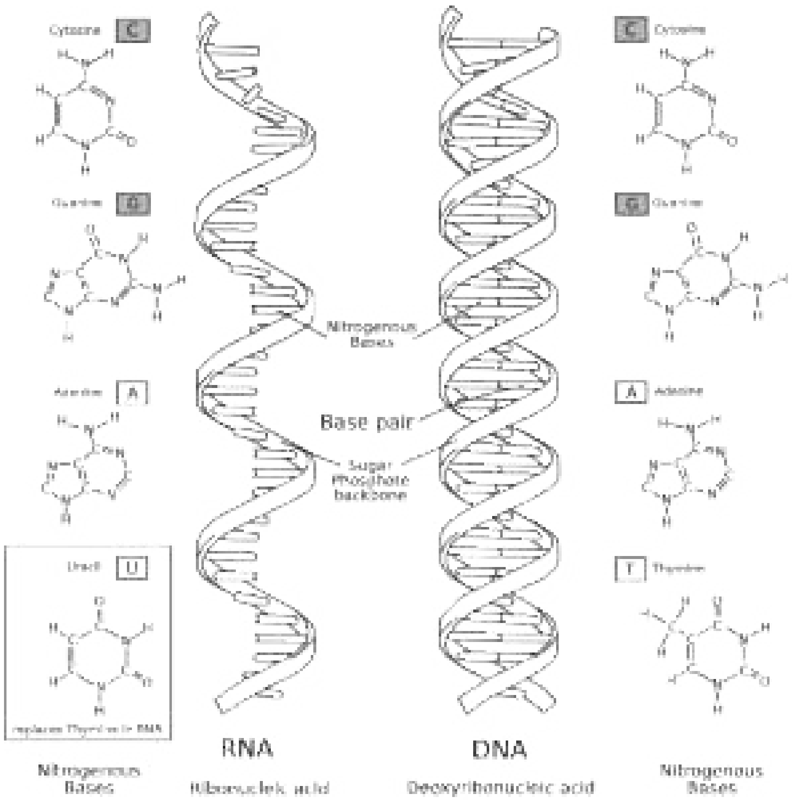


Bernal (1951), first suggested that clay minerals played a key role in chemical evolution and the origins of life because of their ability to take up, protect (against ultraviolet radiation), concentrate, and catalyze the polymerization of, organic molecules.

Clay minerals have been proposed as a likely candidate among solid materials to play roles for life evolution, due to their wide distribution, historical prevalence throughout the timeline of geological and biological events on Earth and their affinity for organic molecules.

For example, clay has been demonstrated to be capable of catalyzing the polymerization of RNA and accelerating the formation of fattyacid vesicles (a protocell model).

Clay -> Selection and Amplification of Chemistry

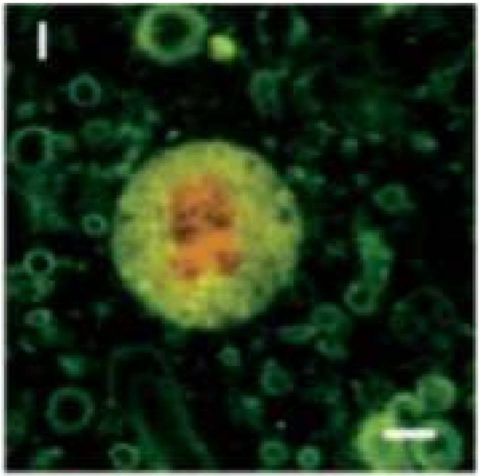


The RNA world refers to the self-replicating ribonucleic acid (RNA) molecules hypothesised to have been the precursors to all current life on Earth.

Supported by several lines of evidence including how RNA was protected on the early earth.

Eventually DNA is thought to have taken over the role RNA in data storage due to its increased stability, while proteins, through a greater variety of monomers (amino acids), replaced RNA's role in specialized biocatalysis.

Smectite clay tends to adsorb organic compounds and this contributes to its ability to catalyze a variety of organic reactions critical to scenarios of life's origins. It has been shown experimentally that RNA molecules bind efficiently to clays and that montmorillonite can catalyze the formation of longer molecules (oligomers), thus lending support to the RNA world hypothesis.



Life on Earth: Fresh clues hint at how the first living organisms arose from inanimate matter, Alonso Ricardo and **Jack W. Szostak**, Scientific American, September 2009, pp. 54-61

(I) Montmorillonite smectite clay coated with Cy3-labeled RNA (red) trapped inside dye-labeled vesicles (green).

Experimental Models of Primitive Cellular Compartments: Encapsulation, Growth, and Division

Martin M. Hanczyc,* Shelly M. Fujikawa,* Jack W. Szostak†

The clay montmorillonite is known to catalyze the polymerization of RNA from activated ribonucleotides. Here we report that montmorillonite accelerates the spontaneous conversion of fatty acid micelles into vesicles. Clay particles often become encapsulated in these vesicles, thus providing a pathway for the prebiotic encapsulation of catalytically active surfaces within membrane vesicles. In addition, RNA adsorbed to clay can be encapsulated within vesicles. Once formed, such vesicles can grow by incorporating fatty acid supplied as micelles and can divide without dilution of their contents by extrusion through small pores. These processes mediate vesicle replication through cycles of growth and division. The formation, growth, and division of the earliest cells may have occurred in response to similar interactions with mineral particles and inputs of material and energy.

24 OCTOBER 2003 VOL 302 SCIENCE www.sciencemag.org

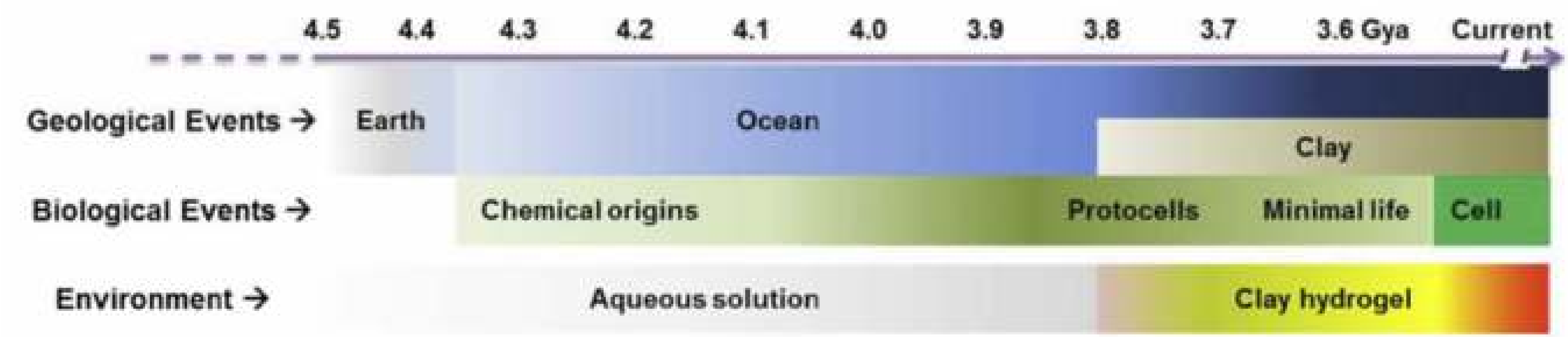
The Szostak Lab

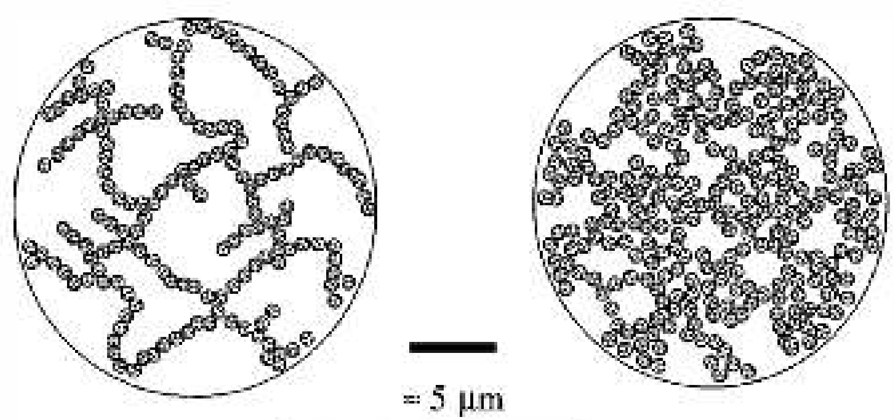
http://molbio.mgh.harvard.edu/szostakweb/

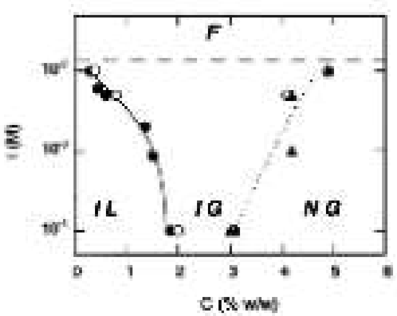
Jack William Szostak : Biologist, Nobel Prize laureate Medicine 2009, Professor of Genetics at Harvard Medical School, and Alexander Rich Distinguished Investigator at Massachusetts General Hospital, Boston

Enhanced transcription and translation in clay hydrogel and implications for early life evolution, Dayong Yang, Songming Peng, Mark R. Hartman, Tiffany Gupton-Campolongo, Edward J. Rice,Anna Kathryn Chang, Zi Gu, G. Q. (Max) Lu & Dan Luo, **SCIENTIFIC REPORTS , 3 : 3165, DOI: 10.1038/srep03165 (2013)**

~ RNA world

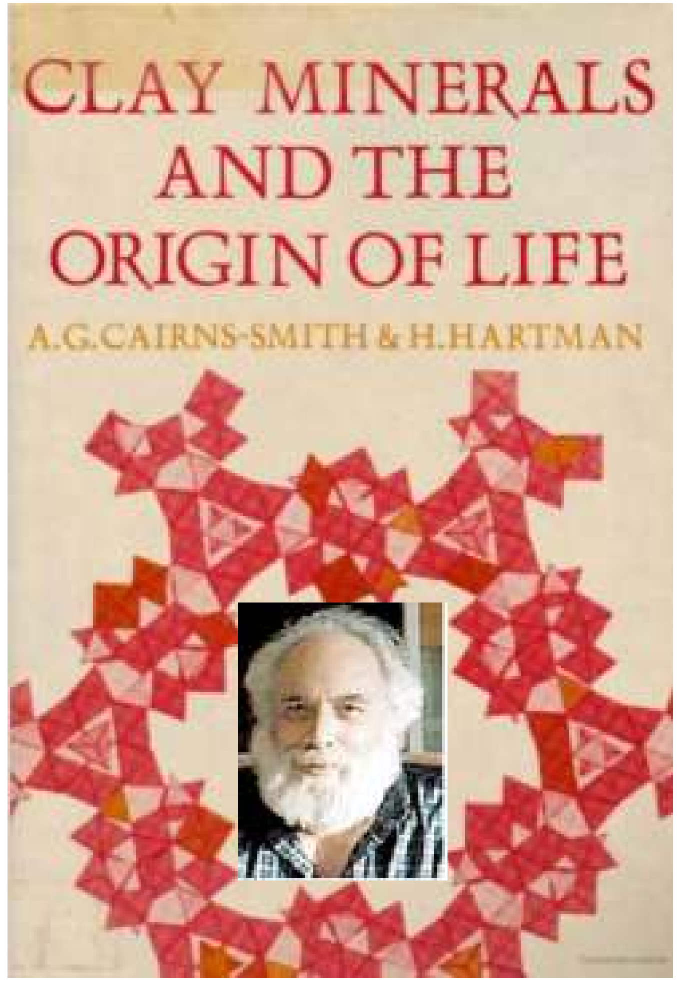


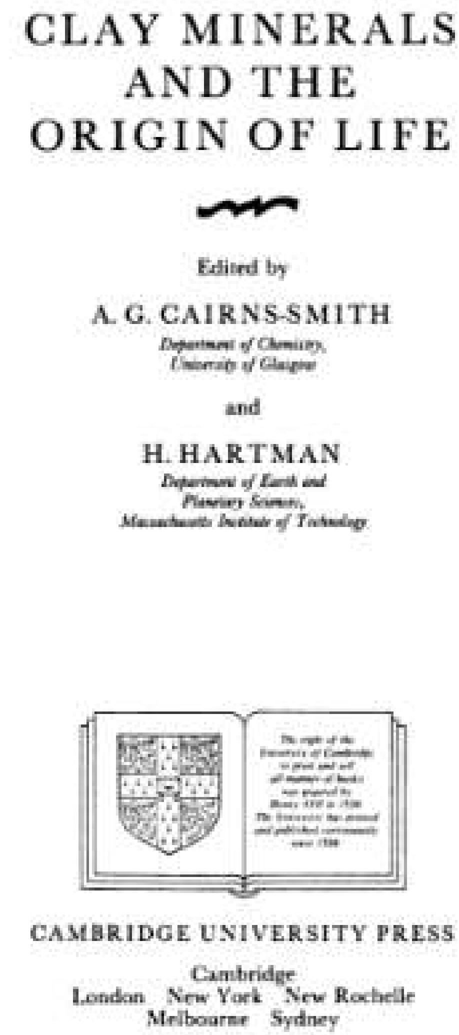




Confinement by clay hydrogel provide an effective environment for localized concentration and protection of nucleic acids.

Bulk-scale clay hydrogel is easily broken down by shear forces into micro-particles, which act as the confinement for biomolecules and biochemical reactions




CLAY MINERALS
AND THE
ORIGIN OF LIFE

Edited by

A. G. CAIRNS-SMITH
Department of Chemistry, University of Glasgow

and

H. HARTMAN
Department of Earth and Planetary Sciences, Massachusetts Institute of Technology

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London New York New Rochelle
Melbourne Sydney

-The physical basis of life, Bernal, J. D. (Routledge & K. Paul London; 1951).

-Mineral Catalysis and Prebiotic Synthesis: Montmorillonite-Catalyzed Formation of RNA, James P. Ferris, ELEMENTS 1, 145-149 (2005)

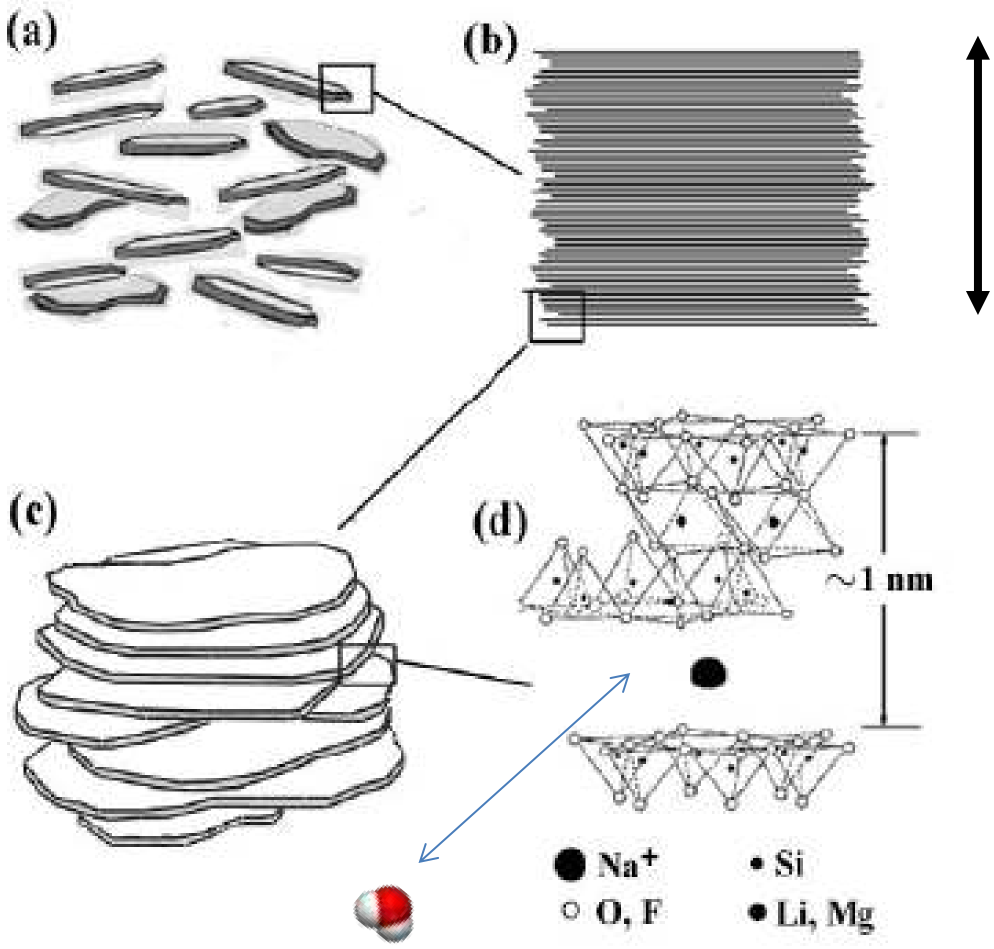
-Role of Clay Minerals in Chemical Evolution and the Origins of Life, Hideo Hashizume in Earth and Planetary Sciences » Geology and Geophysics » "Clay Minerals in Nature - Their Characterization, Modification and Application", book edited by Marta Valaškova and Gražyna Simha Martynkova, ISBN 978-953-51-0738-5, Published: September 12, 2012, DOI: 10.5772/50172

There is lots of work to do, and this is our goal? Liquid or Solid at will? Emerging life?

Molecular interactions with clay particles

Our clay experimental model system:

Q-fluorohectorite synthetic clay: Q_x-$(Mg_{3-x}Li_x)Si_4O_{10}F_2$,
Q is the exchangeable cation (Q = Na^+, Li^+, Ni^{2+}, Fe^{3+}, etc)



Water intercalation:

G. J. da Silva, J. O. Fossum, E. DiMasi, and K. J. Maloy,
Phys. Rev. B 67, 094114 2003.
G. J. da Silva, J. O. Fossum, E. DiMasi, K. J. Maloy, and S. B.Lutnaes,
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R. P. Tenorio, L. R. Alme, M. Engelsberg, J. O. Fossum, and F. Hallwass,
J. Phys. Chem. C 112, 575 2008.
R. P. Tenorio, M.Engelsberg, J. O. Fossum, and G. J. da Silva,
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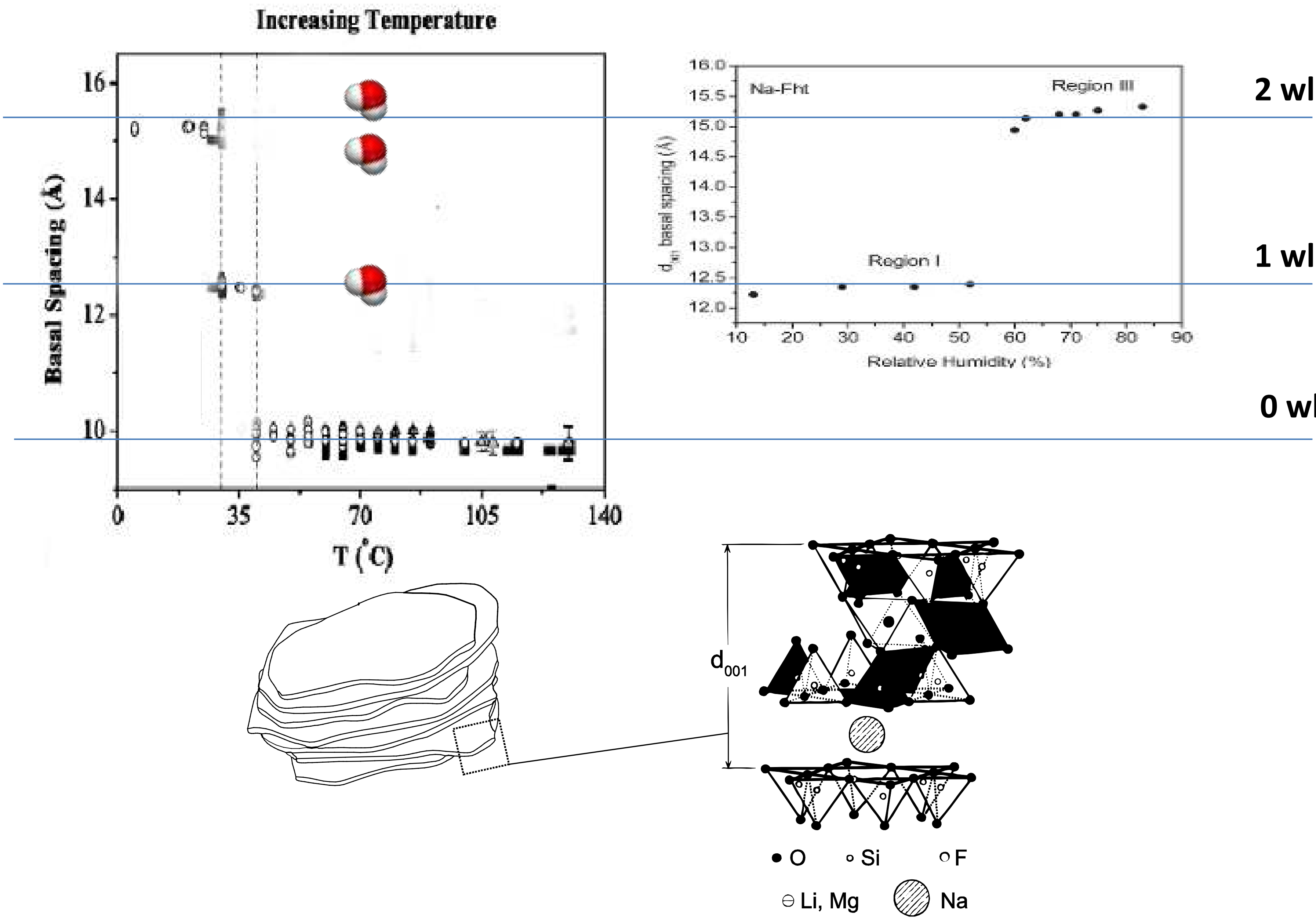
H. Hemmen, L. R. Alme, J. O. Fossum and Y. Meheust,
Phys. Rev. E 82, 036315 2010.
E. L. Hansen, H. Hemmen, D. M. Fonseca, C. Coutant, K. D. Knudsen, T. S. Plivelic, D. Bonn, J. O. Fossum,
Scientific Reports 2, 618 2012

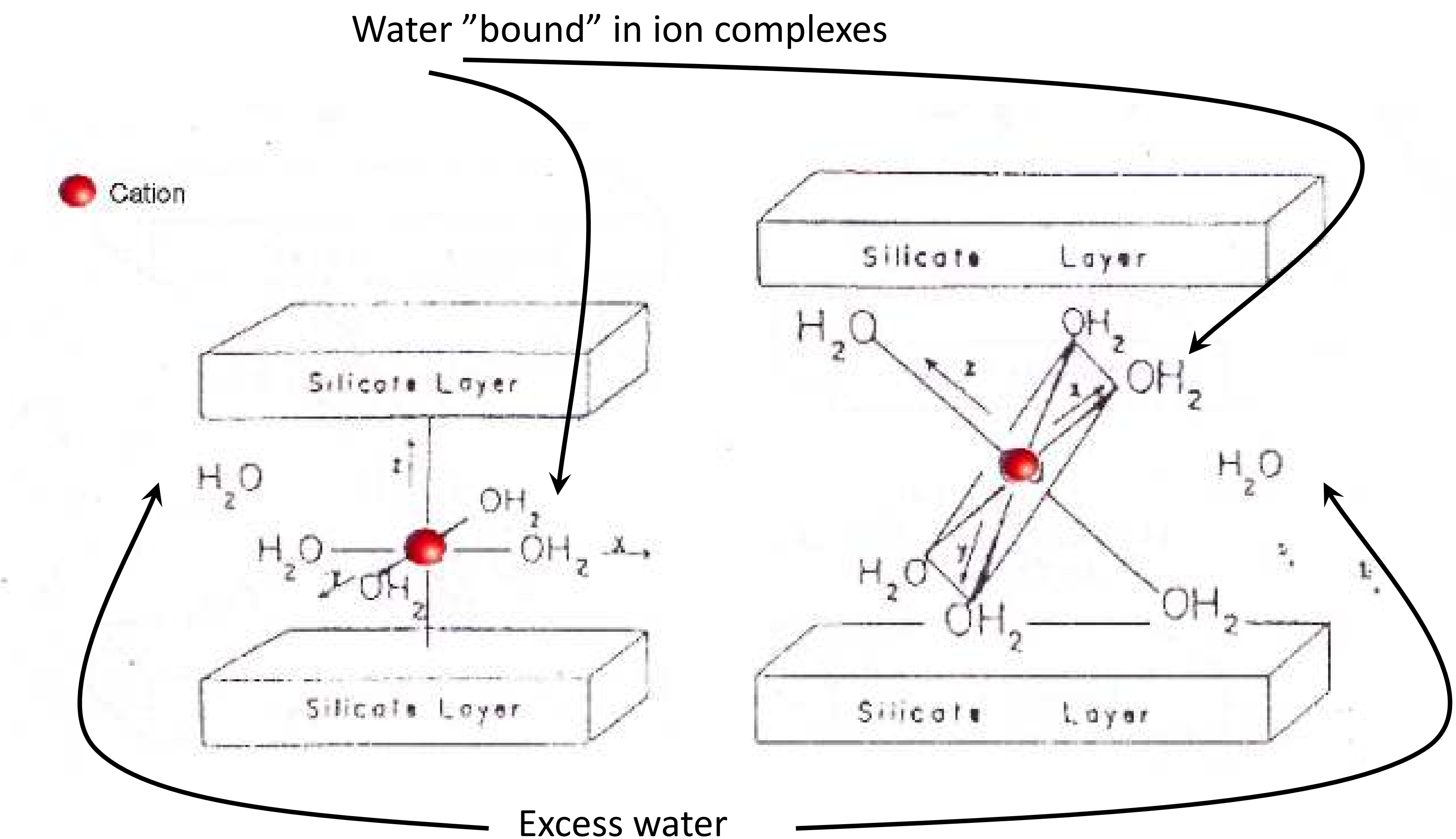
H_2O intercalation controlled by T/RH of sample environment:
Na-fluorohectorite powder in humid air



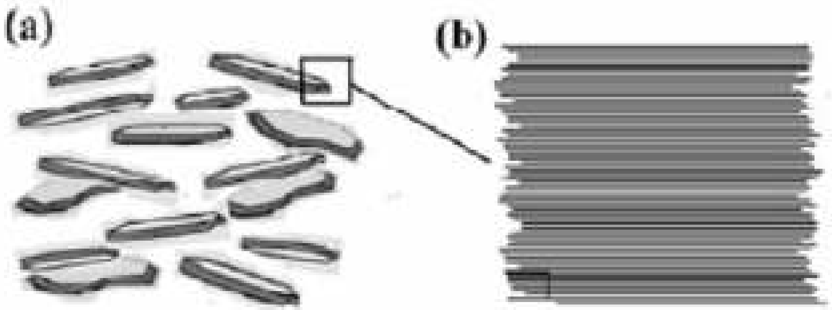
NMR spectroscopy:

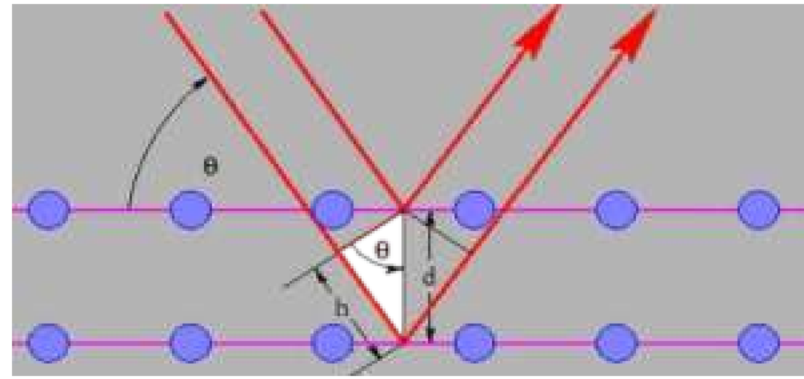
R. P. Tenorio, L. R. Alme, M. Engelsberg, J. O. Fossum, and F. Hallwass, **J. Phys. Chem. C 112, 575 2008.**
R. P. Tenorio, M.Engelsberg, J. O. Fossum, and G. J. da Silva, **Langmuir 26, 9703 2010.**

Two kinds of intercalated water:

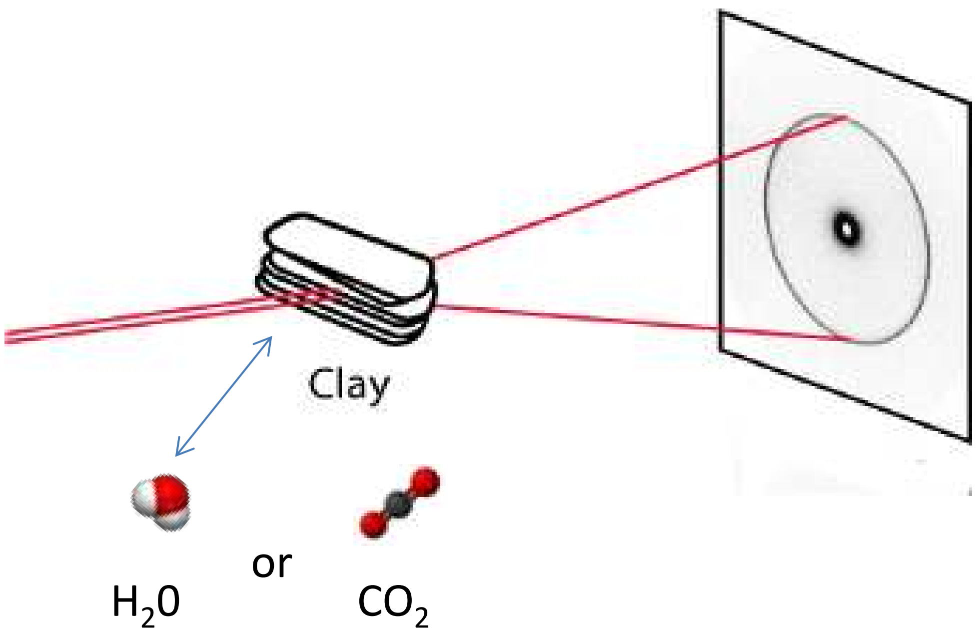


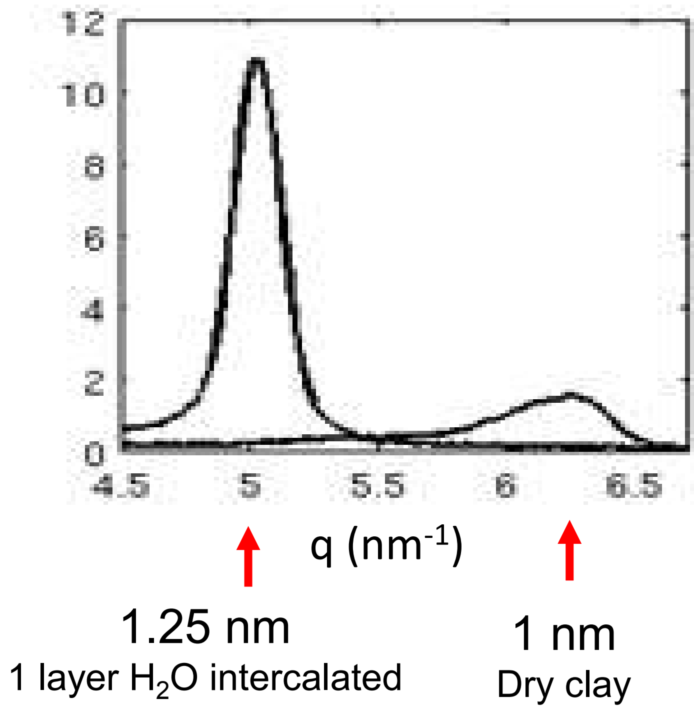
Scattering of X-rays: Bragg's law:



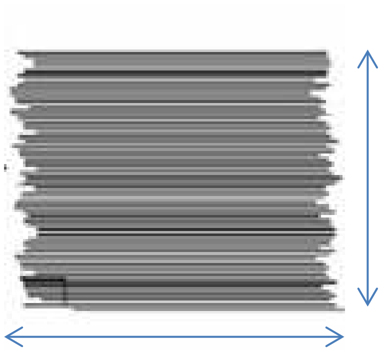


Constructive interference when $2h = 2d\sin\theta = n\lambda$



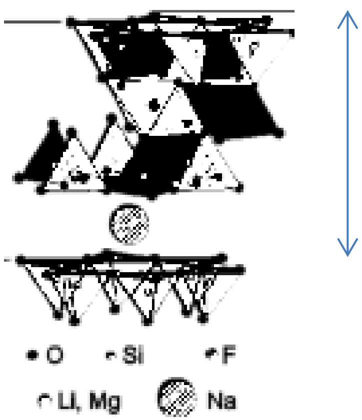


How many “foreign” molecules are captured?



1 m

1 m

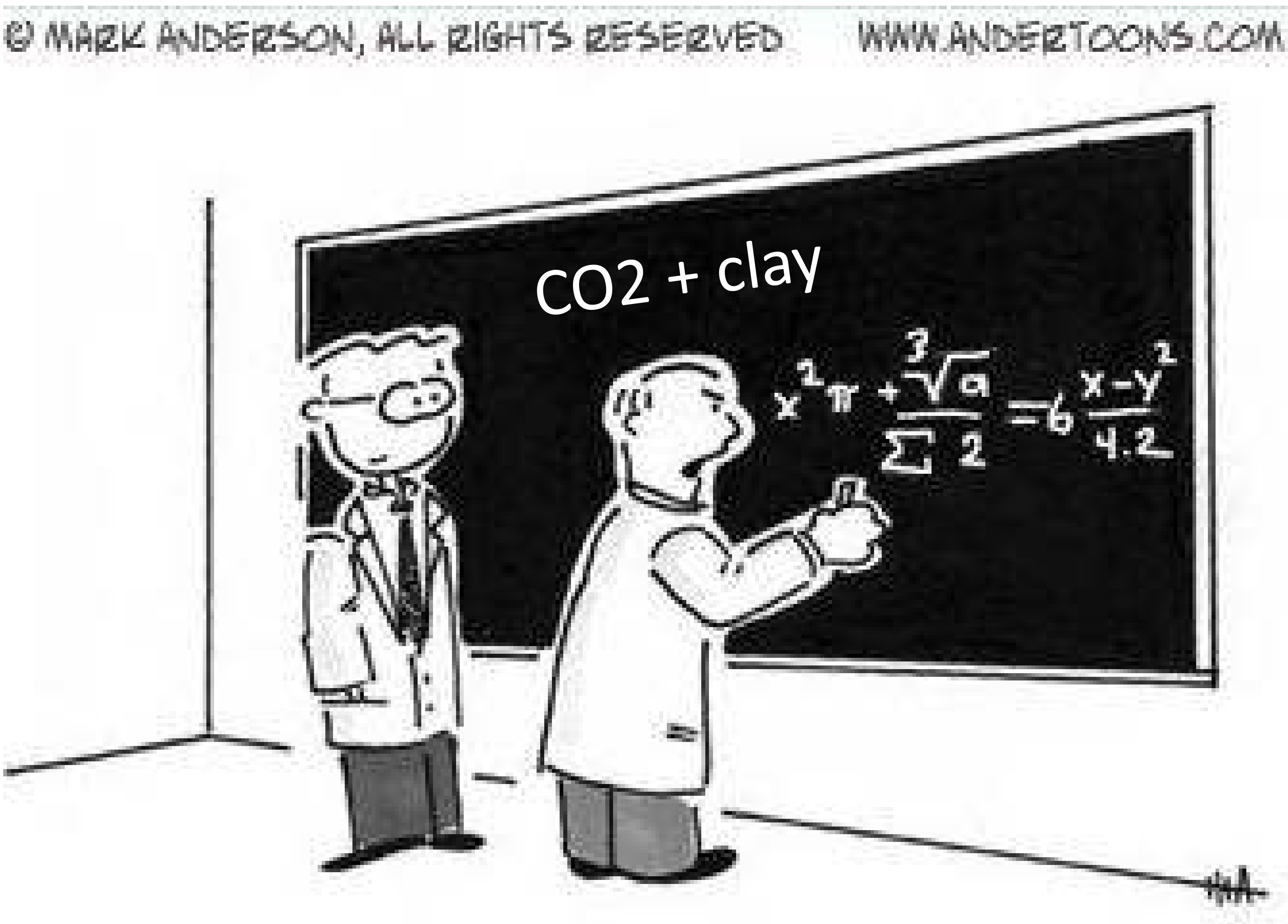


1 nm

In 1 m^3 of compactly packed clay the total clay surface $2x10^9$ m^2 = 2000 $(km)^2$.
The typical packing density of our clay powder is 0.6, so **the total clay surface area available in 1 m^3 of clay powder** is 0.6x2000 $(km)^2$ **~ 1200 $(km)^2$**.

The lateral unit cell size is ~ < 1 $(nm)^2$, and there is about 1.2 monovalent charge compensating monovalent cations per unit cell area in fluorohectorite, i.e.
~1 cation per $(nm)^2$.

Assumption:
~2 “foreign” molecules captured per $(nm)^2$, (NMR: ~ 2 water molecules complexed per cation at ambient conditions),



"It doesn't *have* to be politically correct!"

Before 2012:

J. J. Fripiat, M. I. Cruz, B. F. Bohor, J. Thomas. *Interlamellar adsorpion of carbon dioxide by smectites* Clays Clay Miner. 22, 23, (1974).

The evidence presented in this study clearly shows that CO_2 at about -70 °C penetrates (intercalates) the smectite structure to a degree dependent upon the nature of the replaceable interlayer cation.

Langmuir
Letter
pubs.acs.org/Langmuir
dx.doi.org/10.1021/la204164q | *Langmuir* 2012, 28, 1678–1682

X-ray Studies of Carbon Dioxide Intercalation in Na-Fluorohectorite Clay at Near-Ambient Conditions

Henrik Hemmen,*[†] Erlend G. Rolseth,[†] Davi M. Fonseca,[†,‡] Elisabeth L. Hansen,[†] Jon Otto Fossum,*[†,§] and Tomás S. Plivelic[‡]

[†]Department of Physics, Norwegian University of Science and Technology, Høgskoleringen 5, N-7491 Trondheim, Norway
[‡]Centre for Advanced Study (CAS) at the Norwegian Academy of Science and Letters, Drammensveien 78, N-0271 Oslo, Norway
[‡]MAX IV Laboratory, Lund University, SE-221 00 Lund, Sweden
[§]Department of Cancer Research and Molecular Medicine, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

2012 and later: Large number of publications have appeared on clays + CO_2

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SCIENTIFIC REPORTS | ARTICLE OPEN

Intercalation and Retention of Carbon Dioxide in a Smectite Clay promoted by Interlayer Cations

L. Michels, J. O. Fossum, Z. Rozynek, H. Hemmen, K. Rustenberg, P. A. Sobas, G. N. Kalantzopoulos, K. D. Knudsen, M. Janek, T. S. Plivelic & G. J. da Silva

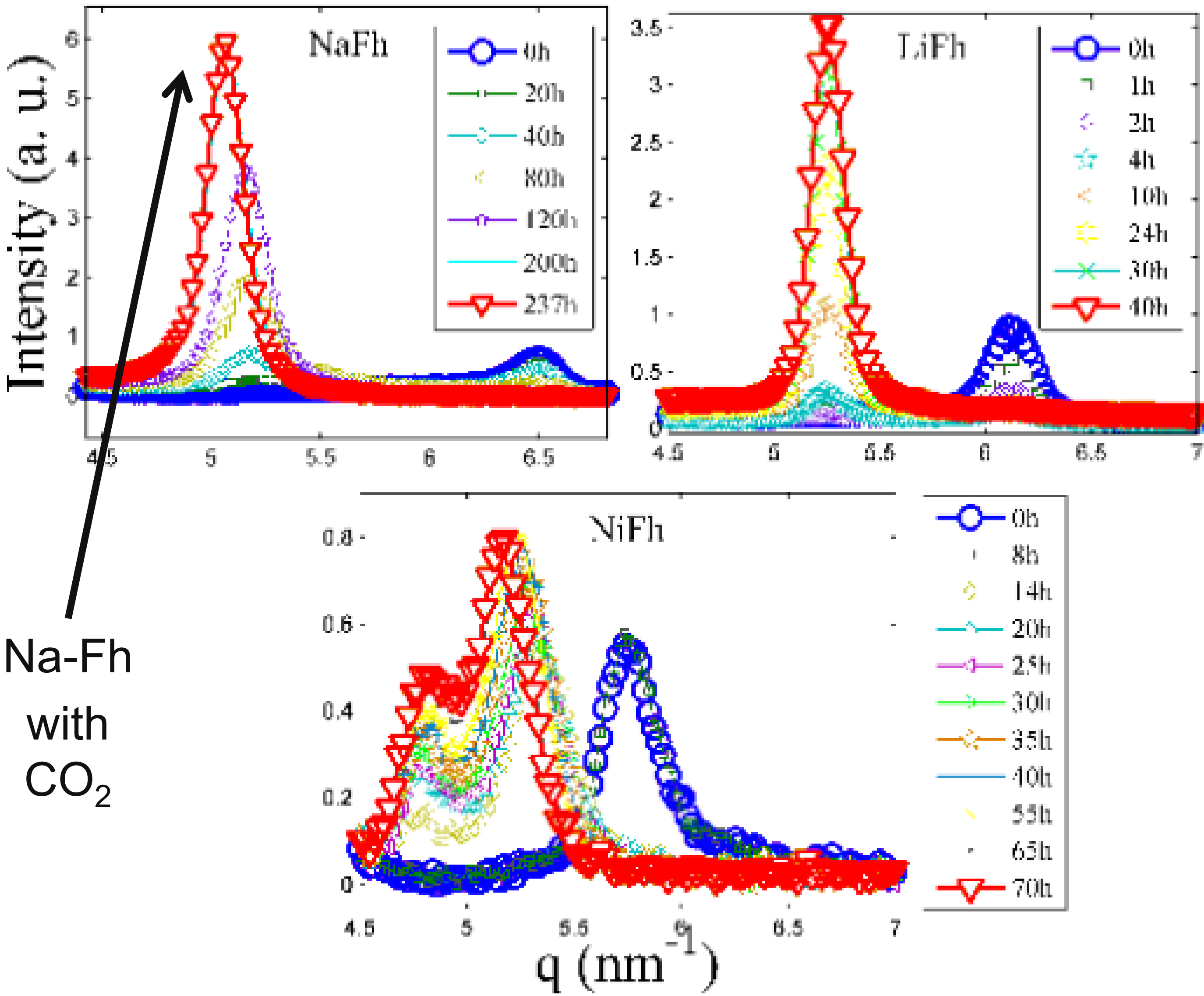
Affiliations | Contributions | Corresponding authors

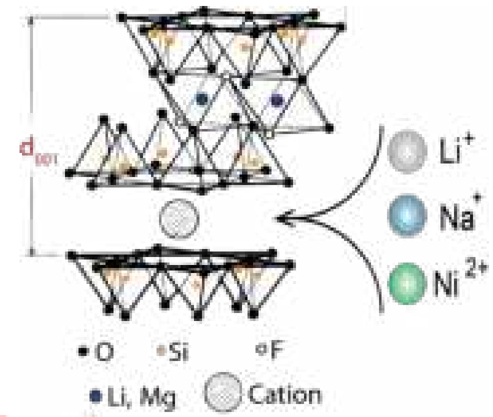
Scientific Reports 5, Article number: 8775 | doi:10.1038/srep08775
Received 12 November 2014 | Accepted 29 January 2015 | Published 05 March 2015

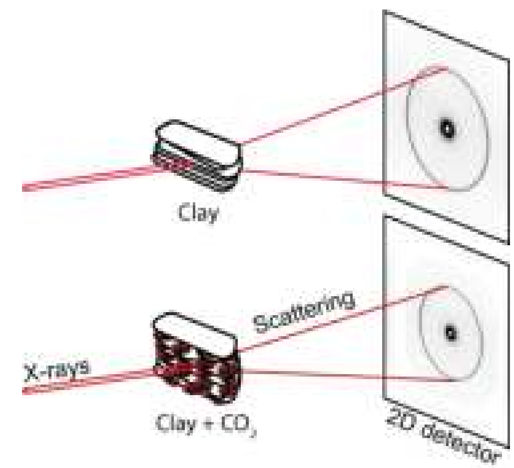
CO_2 intercalation

$P = 20$ bar

$T = -20^{o}C$

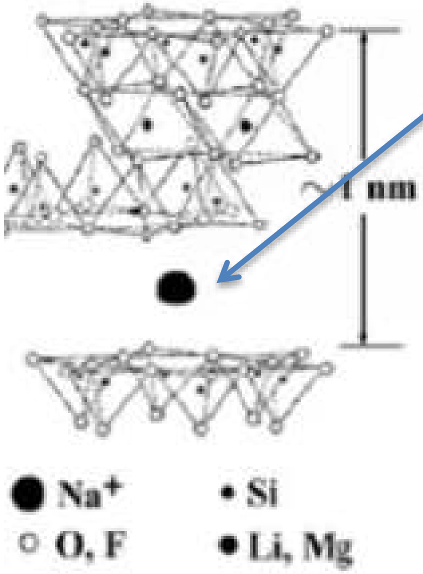


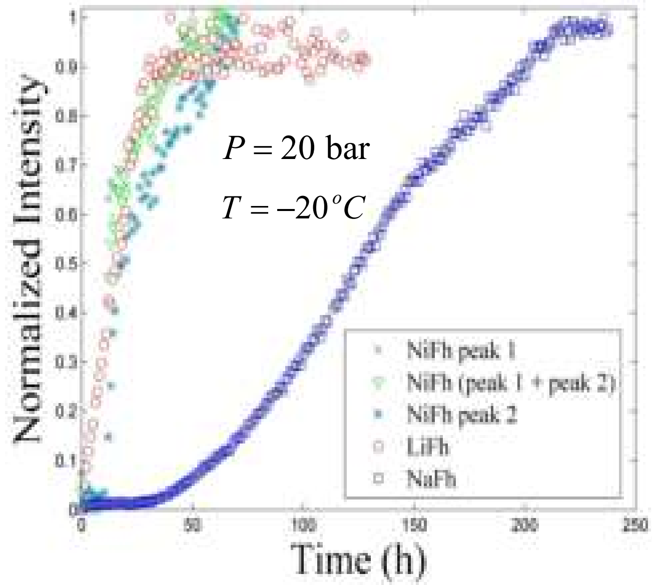




Powders are completelt dehydrated before exposed to CO_2: Blue data points above

Cation dependence



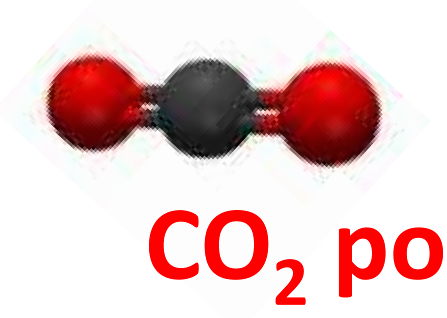


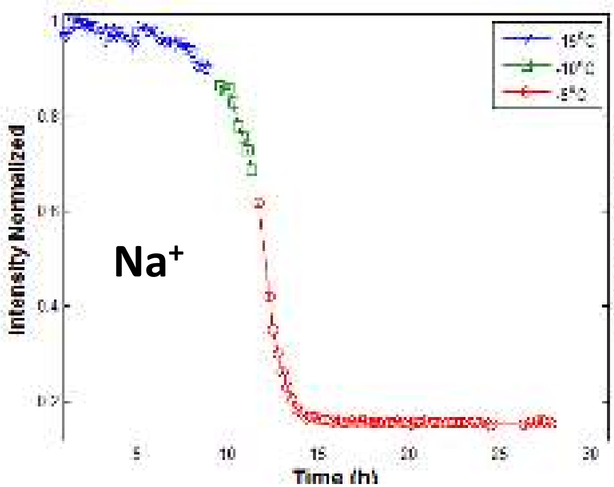
CO_2 Capture:

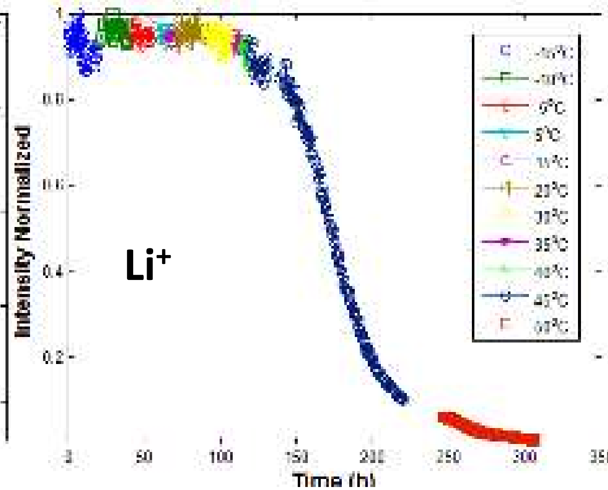
Faster uptake for:
Lower T or higher p

CO_2 Retention:

- N_2 flushing
- Increasing temperature





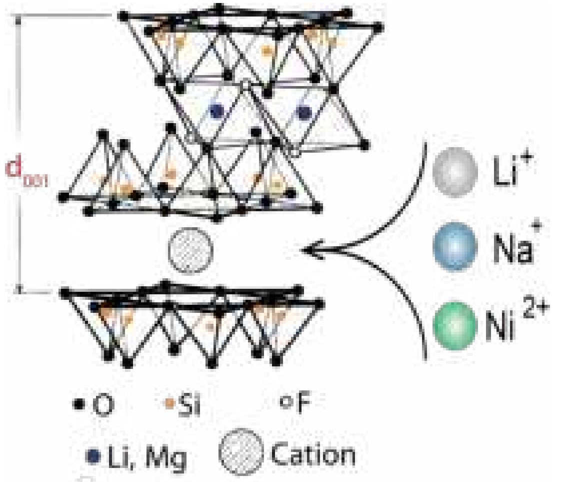


CO_2 polarisibility by Li^+ vs Na^+ ??

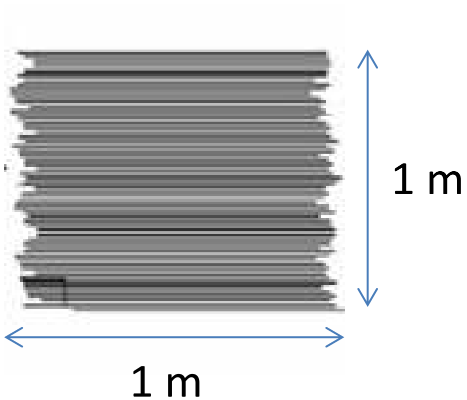
Simplest interpretation:

The clays provide a large surface area available for CO_2 capture.

The cations control capture and release of CO_2 (sometimes modified by clay swelling specifics).



How much CO_2 is captured?



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The typical packing density of our clay powder is 0.6, so **the total clay surface area available in 1 m^3 of clay powder** is 0.6x2000 $(km)^2$ **~ 1200 $(km)^2$**.

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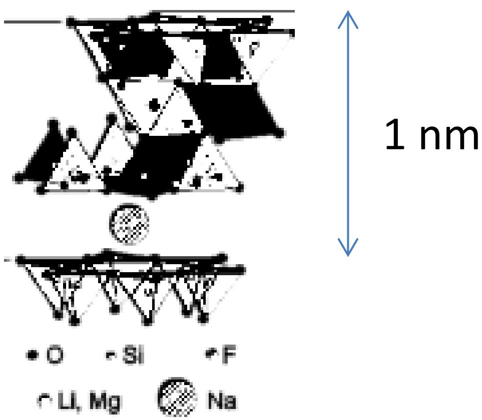

Assumption:
~2 CO_2 molecules captured per cation, (NMR: ~ 2 water molecules complexed per cation at ambient conditions), **which corresponds to ~ 2 CO_2 molecules captured per $(nm)^2$**.

~14% mass increase of the clay when saturated with CO_2, or ~0.22 tons CO_2/m^3 clay.

To check this we did:

pressure composition Temperature (pcT) experiments measure mass increase when sample is loaded with CO_2 => **15% mass increase, confirms assumption above**.

The amount of captured CO_2 for fluorohectorite clay compared with those of other materials.

Material	Efficiency (mmol/g)	Density (g/cm^3)	Captured CO_2 (ton/m^3)
Ideal porous material: Liquid/Solid CO_2			**0.5 (liquid) 1 (solid)**
Benchmark Zeolite 13X	2.5	2.2	**0.14**
"Best"? Zeolite	5	2.2	**0.29**
"Best"? MOF	6	2.0	**0.32**
Fluorohectorite clay (our experiments)	3	2.8	**0.22**

The density of liquid CO_2 is 0.77 ton/m^3 at 56 atm and 20 °C (the density of solid CO_2 is about twice of this) suggesting that ~1 ton CO_2 captured per m^3 is near the theoretical "perfect and unachievable" upper limit for CO_2 capture by any porous material, zeolite, MOF, carbon based, clay, or other.

Our synthetic fluorohectroite clay has about twice as many cations per (nm)^2 as compared to natural clays like bentonite.

Price comparison: Cost of producing synthetic smectites is about 1-10 USD/kg, whereas price of producing MOFs may be about 50 USD/kg.


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Clays in BIONANOTECHNOLOGY

Parrots of the Amazones:

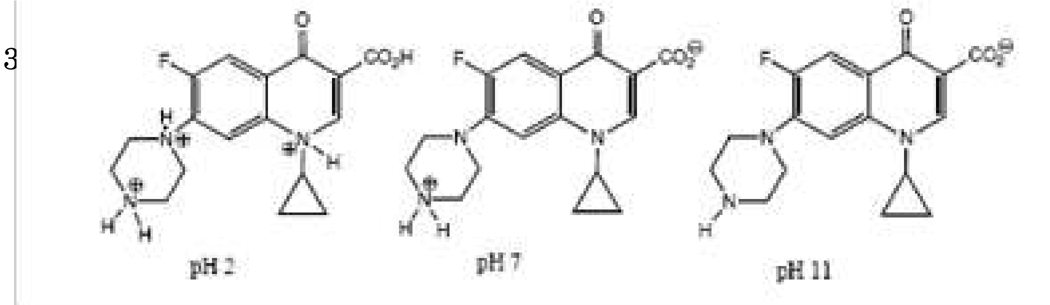
Parrots of the Amazon eat clay at riverbanks for breakfast in order to prevent stomach-ache from alkaloid poisons of the seeds in the fruits they eat for lunch.

Shows that clays may be interesting drug delivery systems

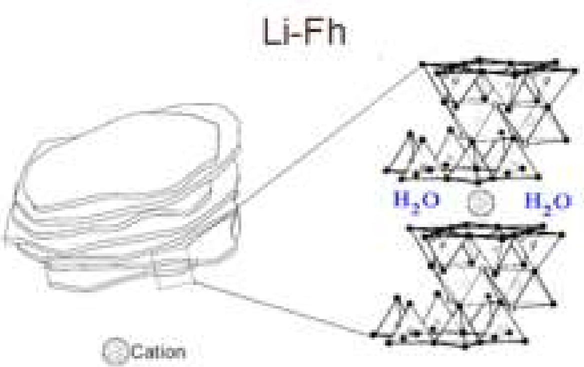
Cipro (ciprofloxacin) is an antibiotic in a group of drugs called fluoroquinolones (flor-o-KWIN-o-lones). It is used to fight bacteria in the body. Cipro is used to treat different types of bacterial infections. It may also be used to prevent or slow anthrax after exposure.

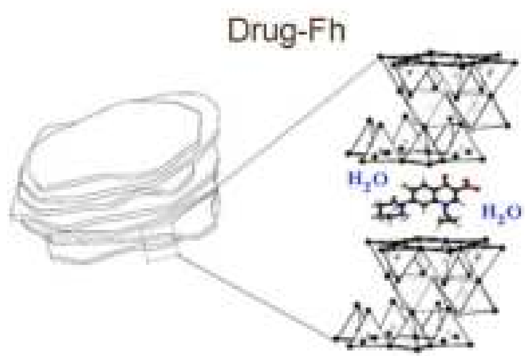
$C_{17}H_{18}FN_3O_3$

Zwitterionic



Positive **Dipole** **Negative**

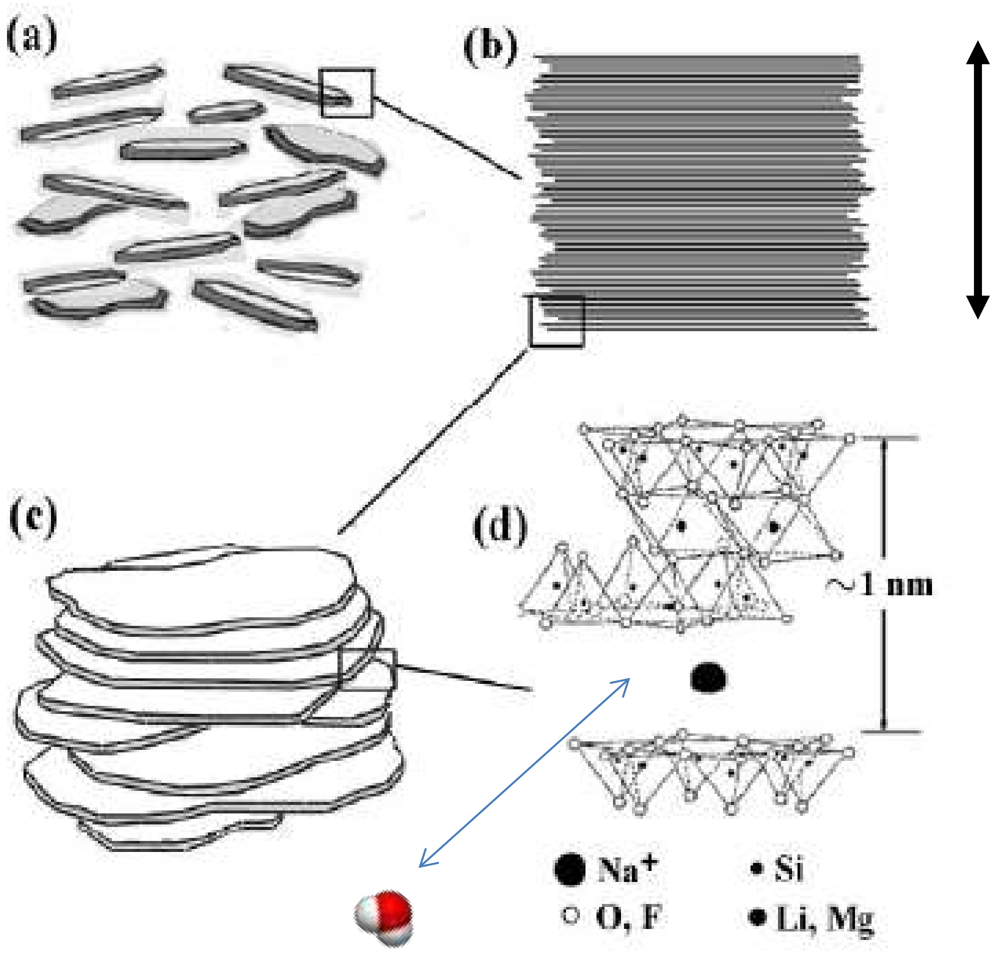




Intercalates by far best for acid pH
Different intercalation mechanism at pH 7?
Rapid release at basic pH
Techniques: XRD, UV-VIS Spectroscopy

Our clay experimental model system:

Q-fluorohectorite synthetic clay: Q_x-$(Mg_{3-x}Li_x)Si_4O_{10}F_2$,
Q is the exchangeable cation (Q = Na^+, Li^+, Ni^{2+}, Fe^{3+}, etc)



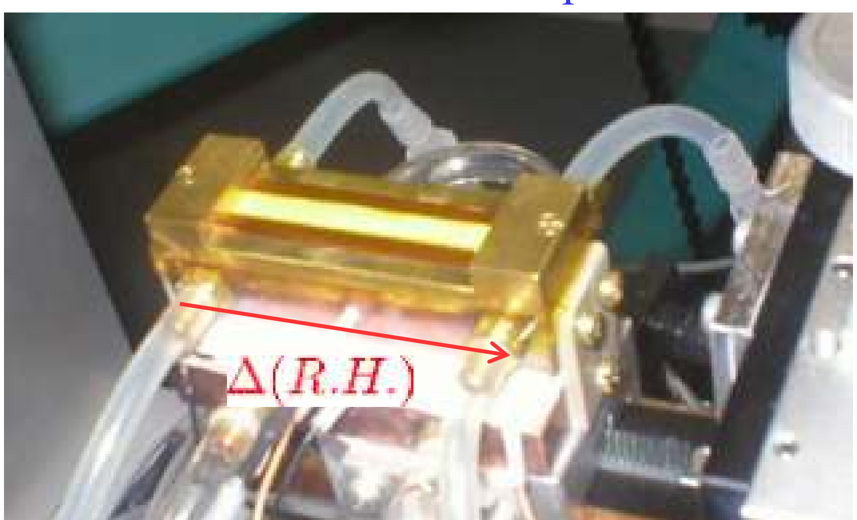
Water intercalation:

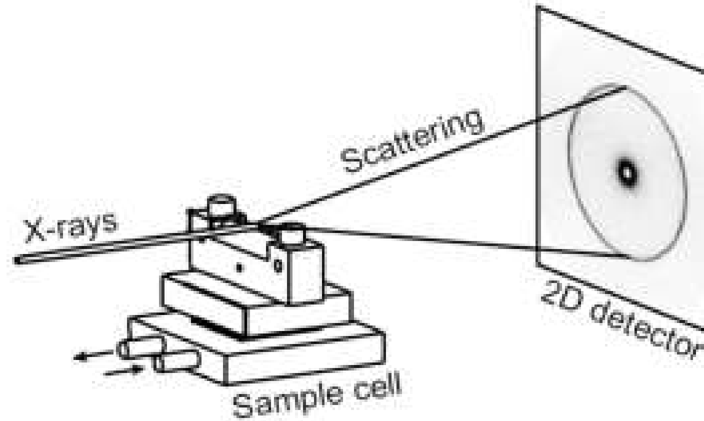
G. J. da Silva, J. O. Fossum, E. DiMasi, and K. J. Maloy,
Phys. Rev. B 67, 094114 2003.
G. J. da Silva, J. O. Fossum, E. DiMasi, K. J. Maloy, and S. B.Lutnaes,
Phys. Rev. E 66, 011303 2002.
R. P. Tenorio, L. R. Alme, M. Engelsberg, J. O. Fossum, and F. Hallwass,
J. Phys. Chem. C 112, 575 2008.
R. P. Tenorio, M.Engelsberg, J. O. Fossum, and G. J. da Silva,
Langmuir 26, 9703 2010.
H. Hemmen, L. R. Alme, J. O. Fossum and Y. Meheust,
Phys. Rev. E 82, 036315 2010.
E. L. Hansen, H. Hemmen, D. M. Fonseca, C. Coutant, K. D. Knudsen,
T. S. Plivelic, D. Bonn, J. O. Fossum,
Scientific Reports 2, 618 2012

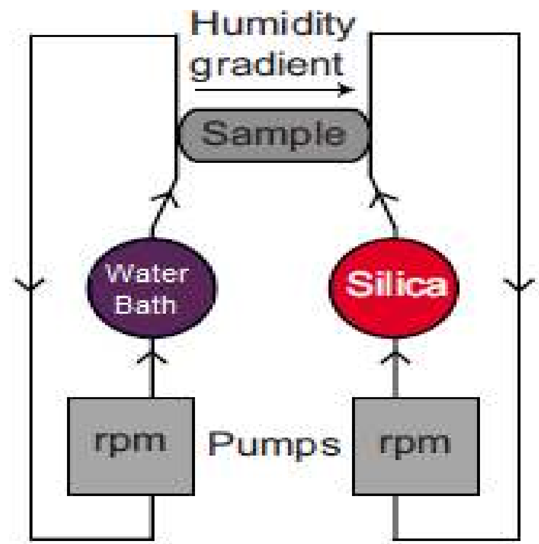
Water Transport Experiment

Only 2 cm of the capillary was observed using x-rays

$\rightarrow$ Diffusive transport



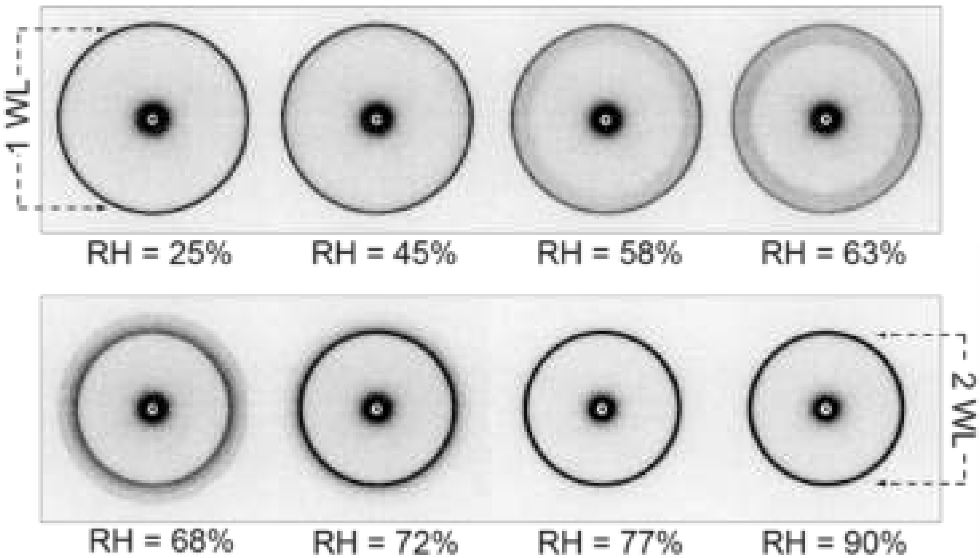


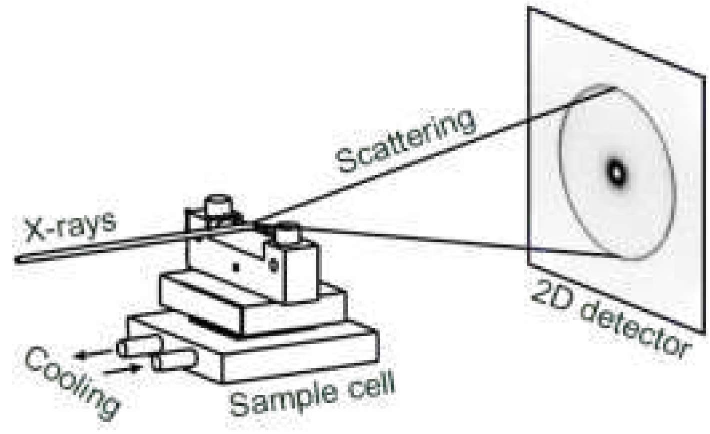


The Fluorohectorite was placed in 1 mm glass capillaries open in both ends, one end exposed to high relative water humidity (96%), the other end exposed to dry air (0.4%)

The sample is scanned forth and back in front of the X-ray beam:

- The quasi-isotropic clay powder diffracts the beam,
- resulting in circular high-intensity rings that denote
- the structural d-spacing d_{001} :

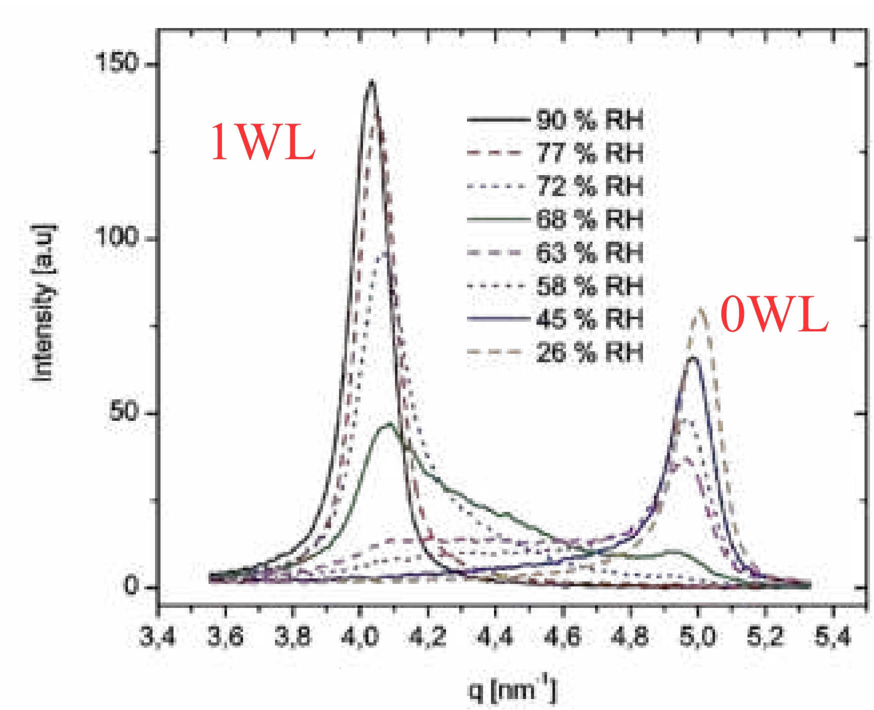




- Azimuthal integration of the rings provides 1D
- diffaction spectra

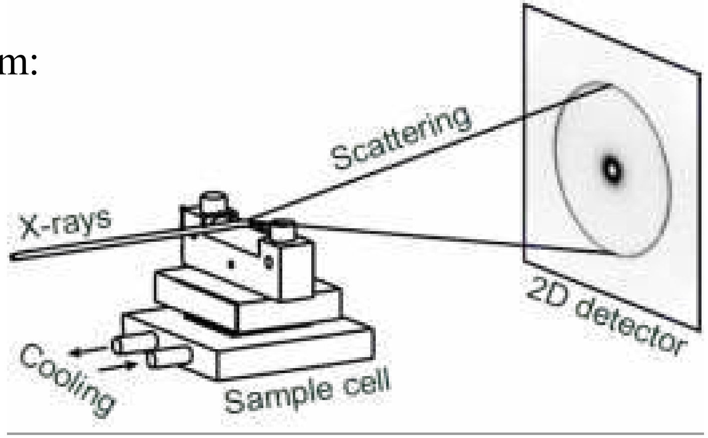
- The position of the peak is related to d_{001} :

$$q = \frac{2\pi}{d}$$ (Bragg's law)

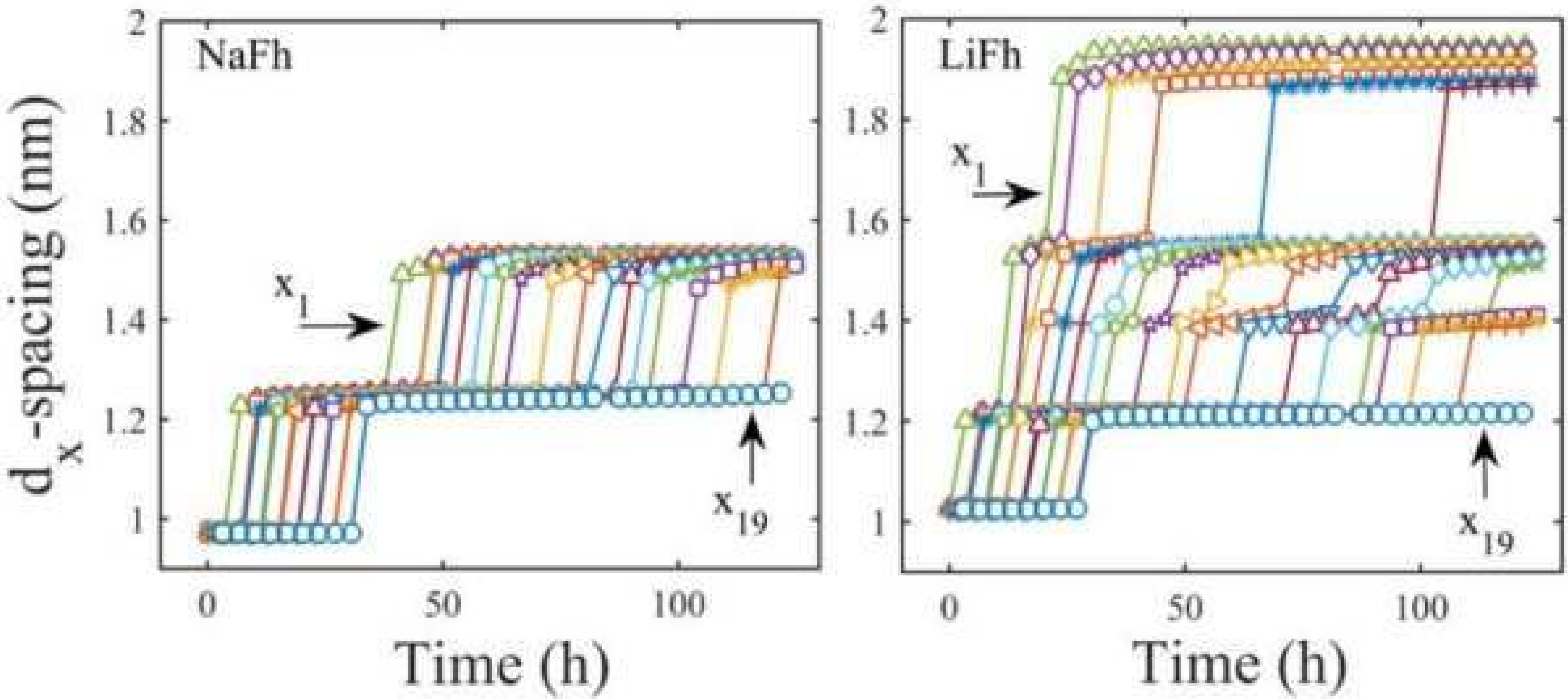


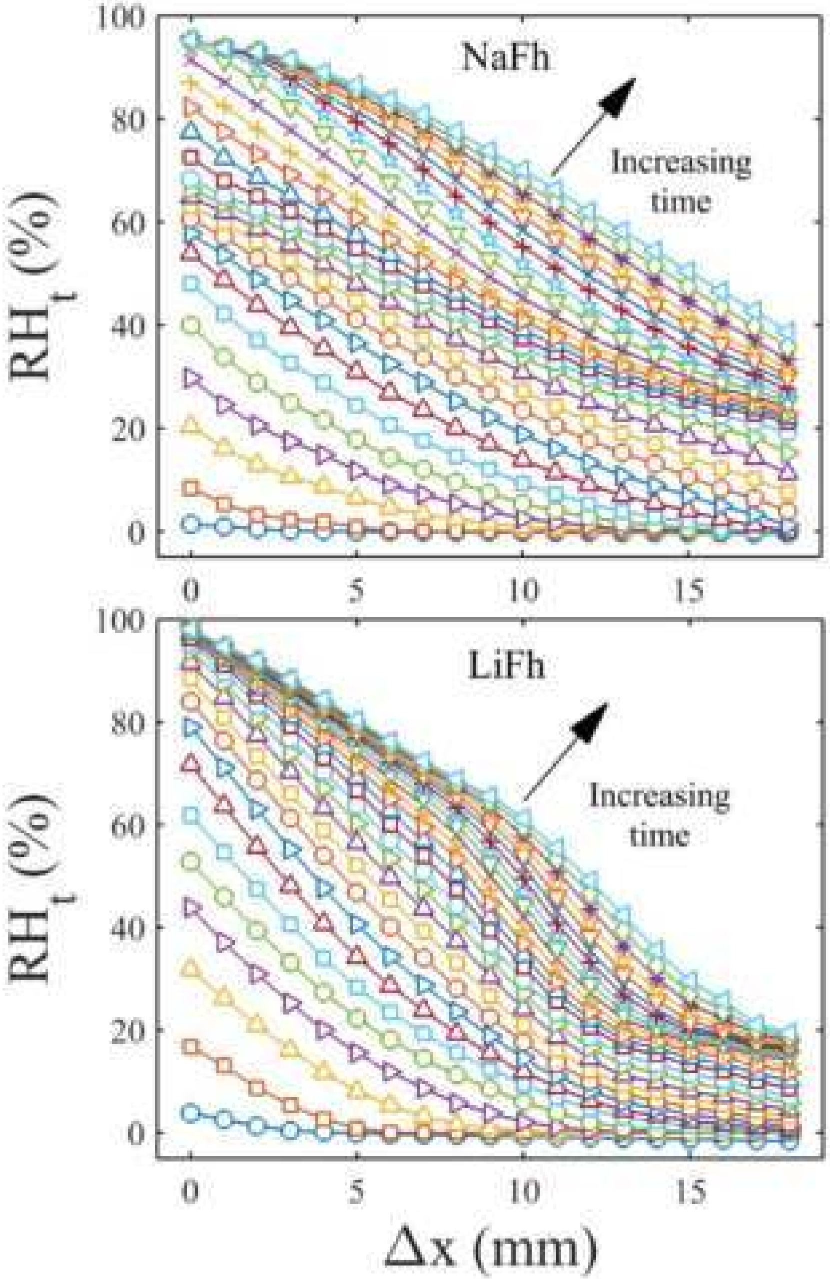
$q = (4\pi/\lambda) \sin\theta$

The sample is scanned forth and back in front of the X-ray beam:



The hydration state is monitored at regular positions
x as a function of time:




NaFh
Increasing time
LiFh
Increasing time
RH_t (%)
RH_t (%)
Δx (mm)
0
20
40
60
80
100
0
5
10
15

Normal diffusion

- Diffusion equation (Fick's law): RH = W

$$\langle (\Delta x)^2 \rangle = 2Dt$$

$$\frac{\partial W(x,t)}{\partial t} = \frac{\partial}{\partial x}\left[D(W) \frac{\partial}{\partial x} W(x,t) \right]$$

- Semi-infinite media:

$$W(x=0,t) = W_0 \quad \forall t > 0$$

$$W(x \to \infty, t) = 0$$

$$W(x, t=0) = 0$$

- Boltzmann transformation $\eta = x / t^{1/2}$

$$-\frac{1}{2}\eta \frac{dW}{d\eta} = \frac{d}{d\eta}\left(D(W) \frac{dW}{d\eta} \right)$$

$$D(W) = -(1/2)\left(\frac{d\eta}{dW}\right) \int_0^W \eta(W) dW'$$

Anomalous diffusion

- Fractal diffusion equation: (Riemann-Louiville fractional derivative)

$$\left\langle (\Delta x)^2 \right\rangle = \frac{2D_\gamma t^\gamma}{\Gamma(1+\gamma)}$$

$$\frac{\partial^\gamma W(x,t)}{\partial t^\gamma} - \frac{t^{-\gamma}}{\Gamma(1-\gamma)} W(x,0) = \frac{\partial}{\partial x}\left(D_\gamma(W) \frac{\partial W(x,t)}{\partial x} \right)$$

$$\frac{\partial^\gamma W(x,t)}{\partial t^\gamma} = \frac{1}{\Gamma(1-\gamma)} \frac{\partial}{\partial t} \int_0^t W(x,t')\,dt' \Big/ (t-t')^\gamma$$

- Boltzmann transformation: $\eta = x / t^\gamma$

$$\frac{1}{\Gamma(1-\gamma)} \int_0^1 \left((1-\gamma) W\left(\eta/u^{\gamma/2}\right) - (\gamma/2)\eta \frac{\partial W\left(\eta/u^{\gamma/2}\right)}{\partial \eta} \right) \frac{du}{(1-u)^\gamma} = \frac{\partial}{\partial \eta}\left(D_\gamma(W) \frac{\partial W}{\partial \eta} \right)$$

$$D_\gamma(W) = \frac{d\eta}{dW} \frac{1}{\Gamma(1-\gamma)} \int_\infty^\eta d\eta' \int_{\eta'}^\infty \left((2/\gamma)(1-\gamma) \frac{W(\xi)}{\xi} - \frac{dW(\xi)}{d\xi} \right) \frac{(\eta'/\xi)^{2/\gamma} d\xi}{\left[1-(\eta'/\xi)^{2/\gamma}\right]^\gamma}$$

→ If valid, the profiles W(η) are independent of the time at which they are recorded !

Anomalous diffusion

- Fractal diffusion equation: (Riemann-Louiville fractional derivative)

$$\left\langle (\Delta x)^2 \right\rangle = \frac{2D_\gamma t^\gamma}{\Gamma(1+\gamma)}$$

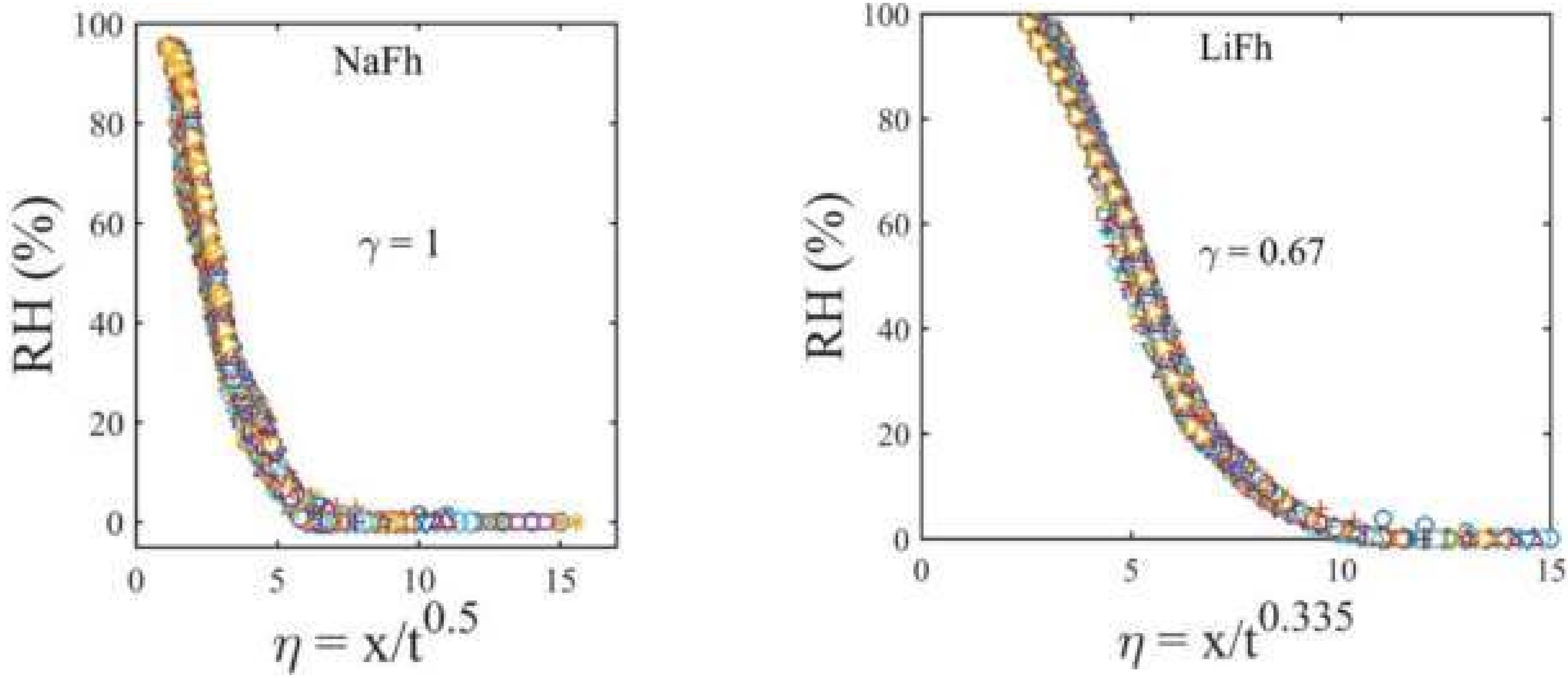
$$\frac{\partial^\gamma W(x,t)}{\partial t^\gamma} - \frac{t^{-\gamma}}{\Gamma(1-\gamma)} W(x,0) = \frac{\partial}{\partial x}\left(D_\gamma (W) \frac{\partial W(x,t)}{\partial x} \right)$$

$$\frac{\partial^\gamma W(x,t)}{\partial t^\gamma} = \frac{1}{\Gamma(1-\gamma)} \frac{\partial}{\partial t} \int_0^t W(x,t') dt' / (t-t')^\gamma$$

Signification of γ:

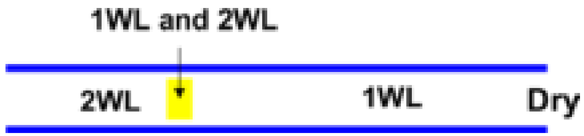
→Reduces to the standard diffusion equation for γ=1
→γ>1 indicates a superdiffusive behavior
→γ<1 indicates a subdiffusive behavior

Using the values γ values inferred from the scaling of the intercalation fronts:

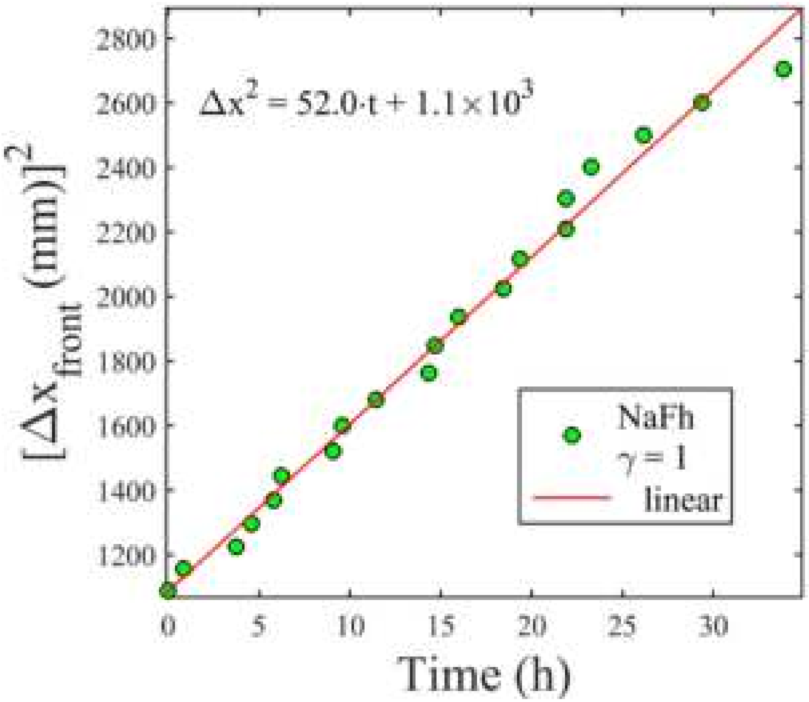


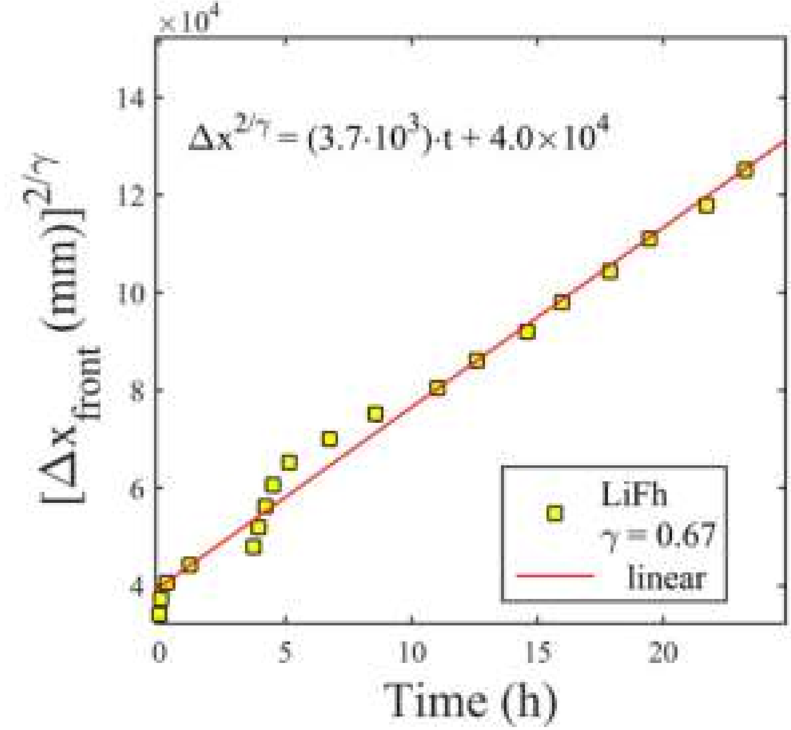
→Suggests anomalous transport for LiFh, normal transport for NaFh
→We now need to consider the concentration field in the mesoporous space

The longitudinal position of the hydration front is monitored as a function of time:



The position of the intercalation front is monitored as a function of time





→Suggests anomalous transport for LiFh, normal transport for NaFh
→We now need to consider the concentration field in the mesoporous space

Time it takes to diffuse 1 m:
NaFh: $t_{1meter} \approx 26$ hours/($2600 * 10^{-6}$) $\approx 10^4$ hours $\approx$ **1 year**
LiFh: $t_{1meter} \approx 24$ hours/($12 * 10^4 * 10^{-9}$) $\approx 2 * 10^5$ hours $\approx$ **20 years**

Permanent and safe storage of nuclear waste

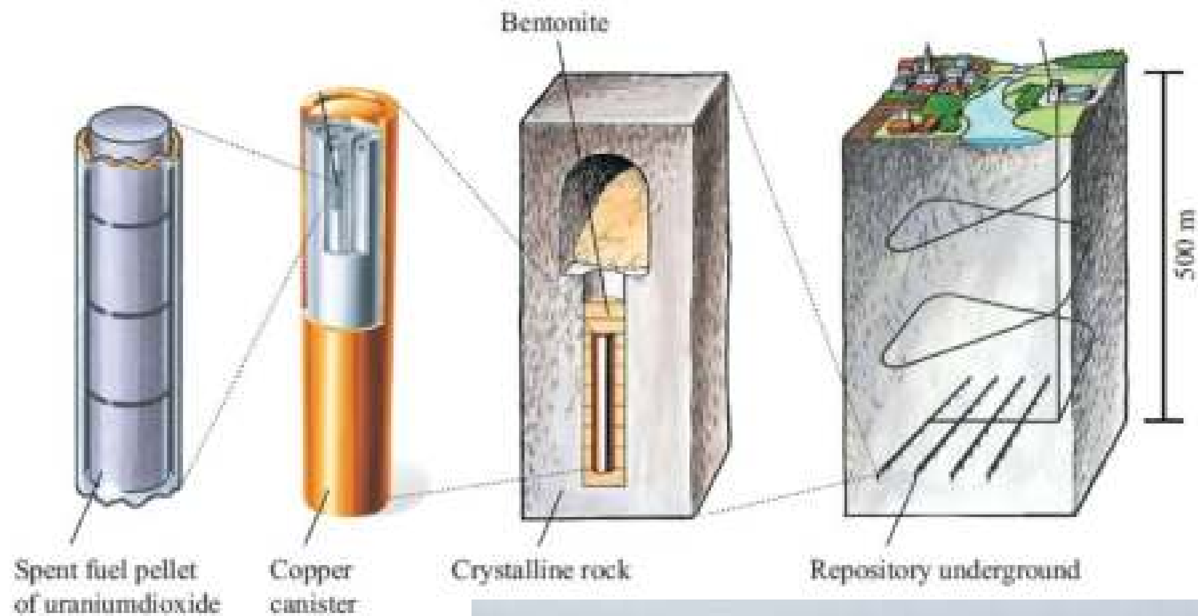
Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering Aktiebolag, abbreviated **SKB**):
Swedish demand for clays as nuclear waste barriers amounts to about one shipload per year.

The Bentonite Barrier

Swelling properties, redox chemistry and mineral evolution

P. Daniel Svensson

LUND UNIVERSITY



DOCTORAL DISSERTATION
by due permission of the Faculty of Engineering, Lund University, Sweden.
To be defended in public at the Center for Chemistry and Chemical Engineering, Lecture Hall K:C, on March 9, 2015, at 13:15.

Faculty opponent
Prof. Jon Otto Fossum, Norwegian University of Science and Technology

Synthetic clays?

New development of, or enhancing existing, forestry or agriculture for CO_2 capture and improved living conditions

NTNU

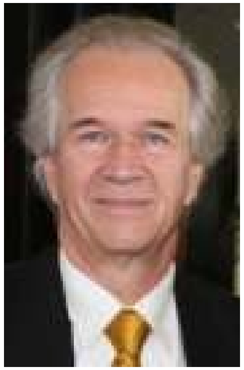
Trees or agriculture in Sahara or similar dry environments? For large scale CO_2 capture?

www.desertcontrol.com

Kristian P. Olesen

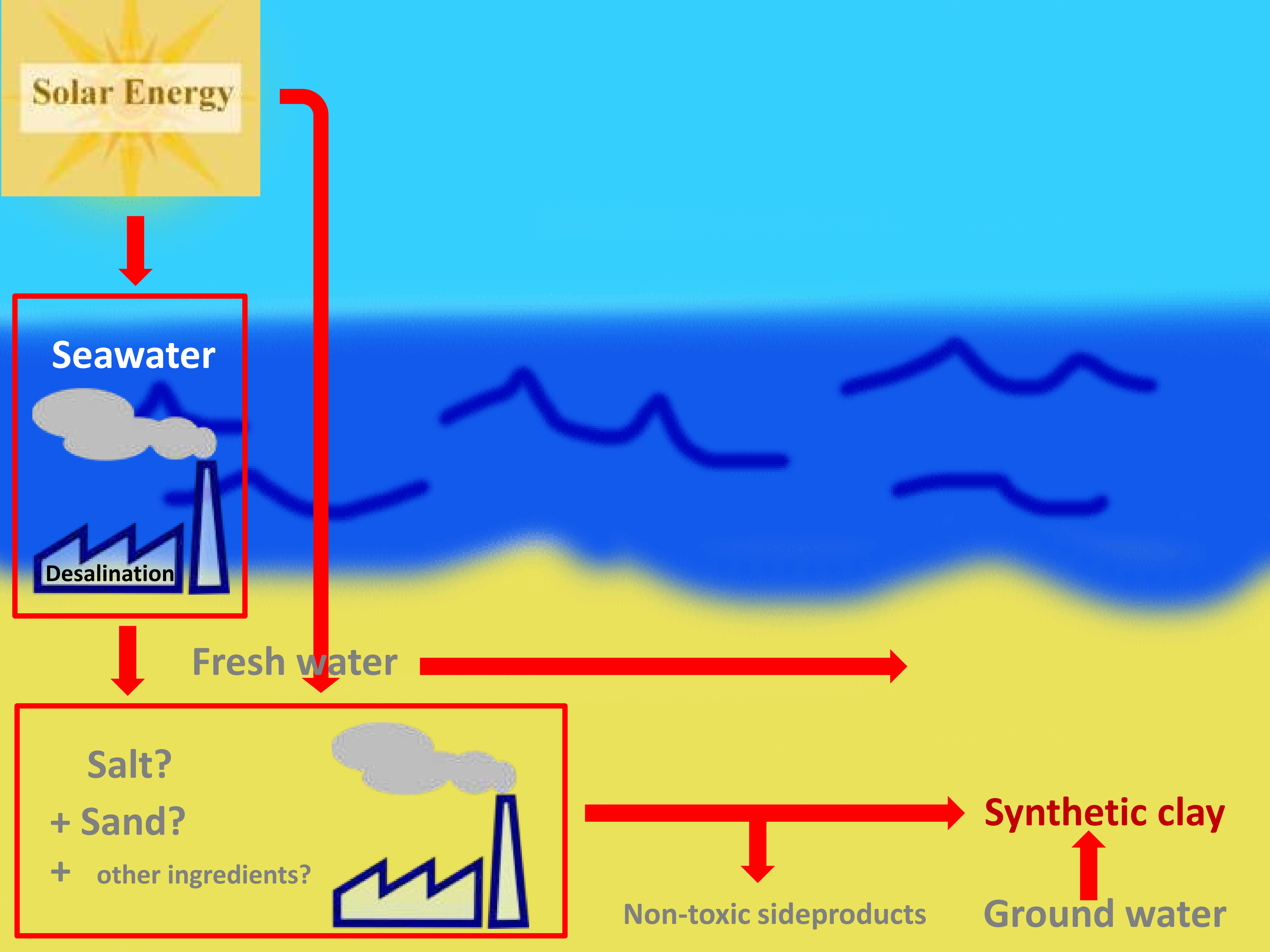
CEO

Patent Holder

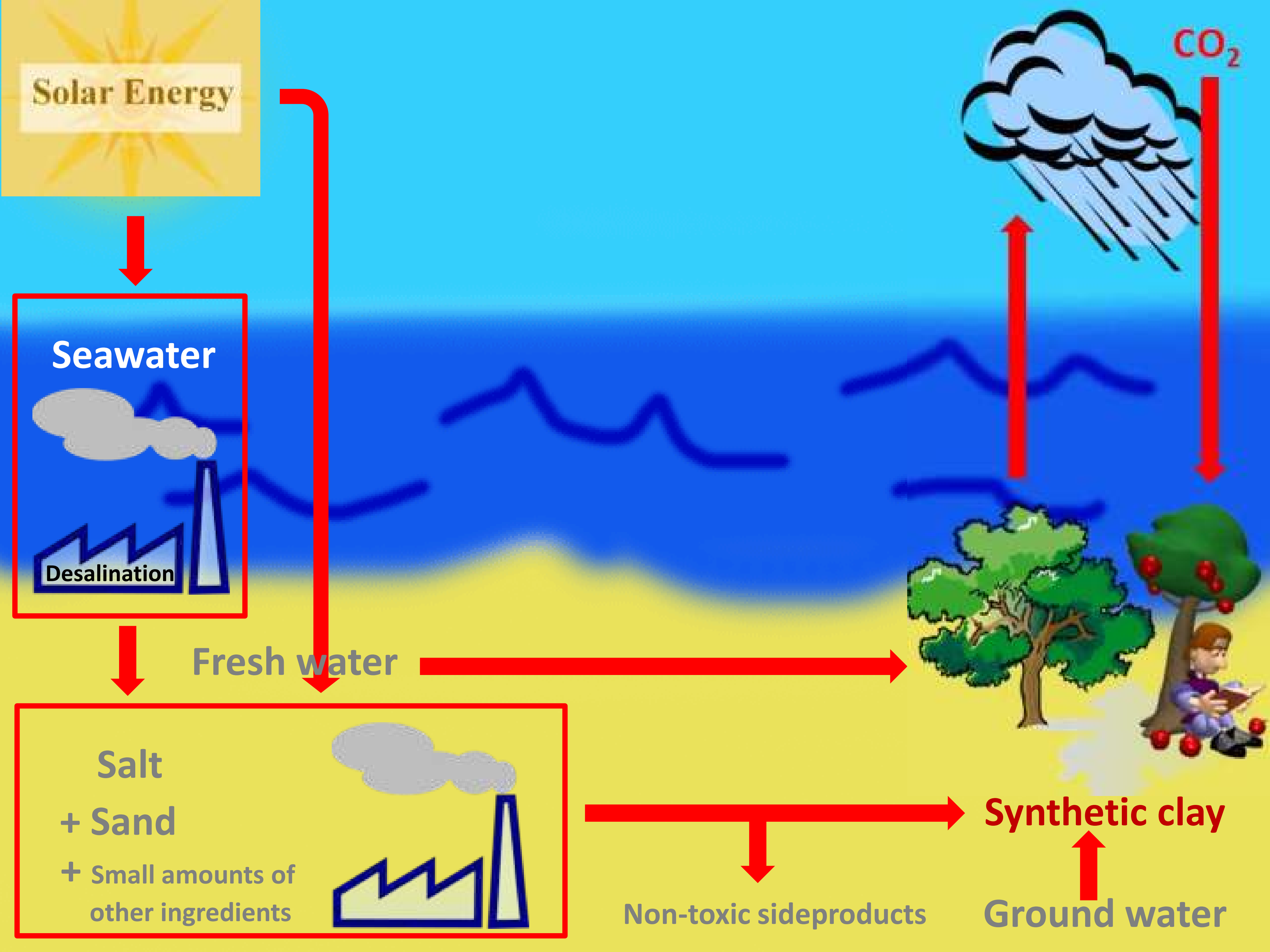


Cover the sand with a layer of clay aqueous suspension and add fertilizer in order to capture the evaporating otherwise excaping ground water? (www.desertcontrol.com)

Sinai Desert test site: Before and after soil treatment with NanoClay



Solar Energy
Seawater
Desalination
Fresh water
Salt?
+ Sand?
+ other ingredients?
Synthetic clay
Non-toxic sideproducts
Ground water



Solar Energy
Seawater
Desalination
Fresh water
Salt
+ Sand
+ Small amounts of other ingredients
Non-toxic sideproducts
Synthetic clay
Ground water
CO_2

Clay based electronics:

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Archive > Volume 516 > Issue 7529 > Letters > Article

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NATURE | LETTER

日本語要約

Conductive two-dimensional titanium carbide 'clay' with high volumetric capacitance

Michael Ghidiu, Maria R. Lukatskaya, Meng-Qiang Zhao, Yury Gogotsi & Michel W. Barsoum

Department of Materials Science and Engineering, and A. J. Drexel Nanomaterials Institute, Drexel University, Philadelphia, Pennsylvania 19104, USA

Nature **516**, 78–81 (04 December 2014) | doi:10.1038/nature13970

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Quasi-Solid Electrolytes for High Temperature Lithium Ion Batteries

Kaushik Kalaga[†], Marco-Tulio F. Rodrigues[†], Hemtej Gullapalli[†], Ganguli Babu[‡], Leela Mohana Reddy Arava[*‡], and Pulickel M. Ajayan[*†]

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Publication Date (Web): November 4, 2015

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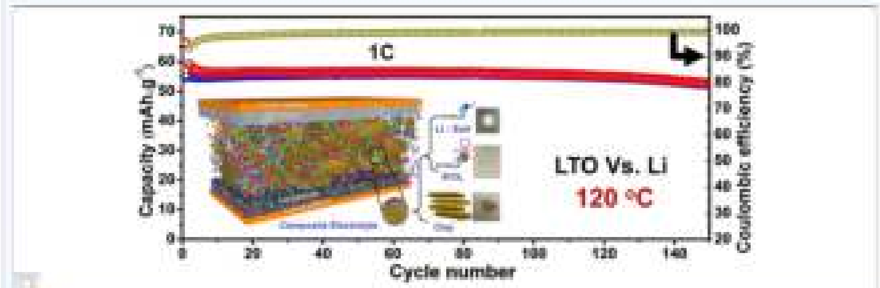
Abstract

Jump to a section



Rechargeable batteries capable of operating at high temperatures have significant use in various targeted applications. Expanding the thermal stability of current lithium ion batteries requires replacing the electrolyte and separators with stable alternatives. Since solid-state electrolytes do not have a good electrode interface, we report here the development of a new class of quasi-solid-state electrolytes, which have the structural stability of a solid and the wettability of a liquid. Microflakes of clay particles drenched in a solution of lithiated room temperature ionic liquid forming a quasi-solid system has been demonstrated to have structural stability until 355 °C. With an ionic conductivity of ~3.35 mS cm^{-1}, the composite electrolyte has been shown to deliver stable electrochemical performance at 120 °C, and a rechargeable lithium battery with $Li_4Ti_5O_{12}$ electrode has been tested to deliver reliable capacity for over several cycles of charge–discharge.

Keywords: high temperature energy devices, quasi-solid electrolytes, lithium ion battery, ionic liquids, clay composites, lithium titanate

Clay based electronics?

Nanolayered materials beyond graphene: Heterostructures and metamaterials

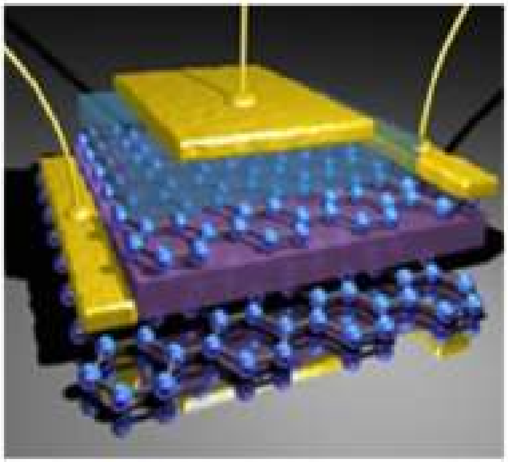


Figure 1:
Principal sketch of our graphene-clay electronic device, manually assembled at Univ. Manchester in Prof. Novoselov's group, using manual exfoliation techniques developed in that laboratory.

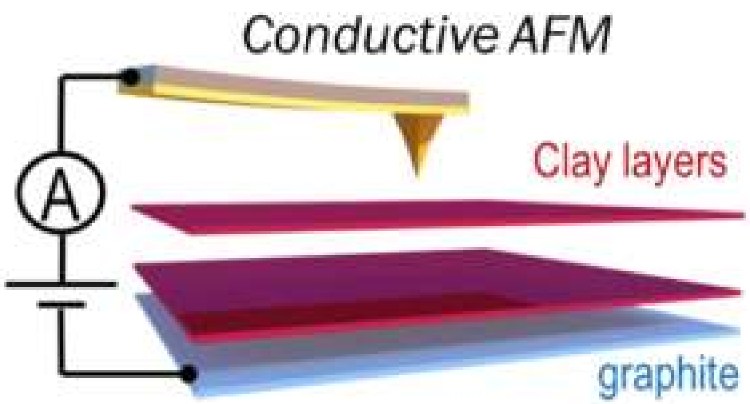


Figure 2:
Principle sketch of experimental set-up for measurements of IV-characteristic of our prototype graphene-clay device. The experiments were performed at Univ. Manchester in Prof. Novoselov's group.

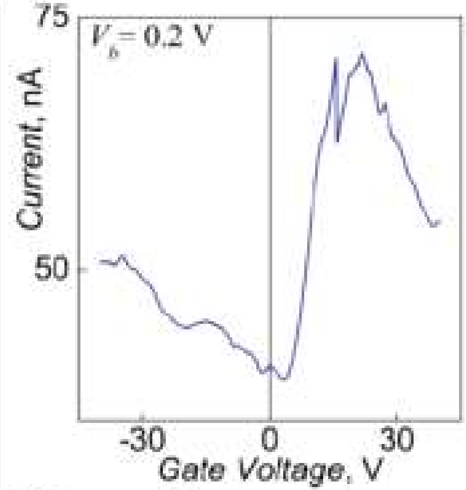
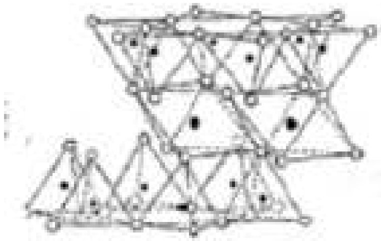


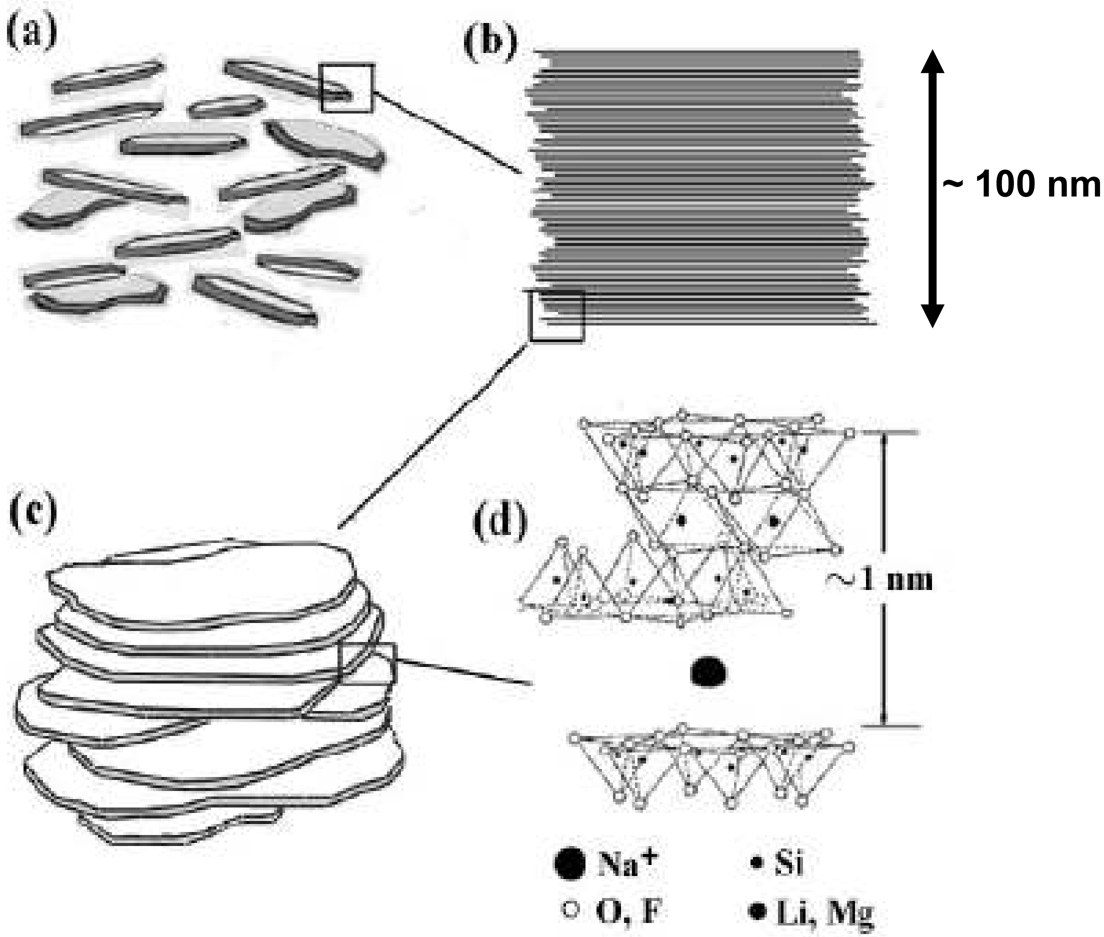
Figure 3:
Preliminary tunneling I-V characteristics for our prototype graphene-clay device. The experiments performed at Univ. Manchester.

Electronic and magnetic properties along or perpendicular to the clay sheets etc.



Our clay experimental model system:

Q-fluorohectorite synthetic clay: Q_x-$(Mg_{3-x}Li_x)Si_4O_{10}F_2$,
Q is the exchangeable cation (Q = Na^+, Li^+, Ni^{2+}, Fe^{3+}, etc)



Sources of fluorohectorite:

Corning Inc.
$x \approx 0.6 \pm 0.05$
Lateral ~ 0.5-10 μm
(incl. 20% known impurities)

Inorg. Chem.
Univ. Bayreuth, Germany
Prof. Josef Breu
$x = (0.2 <\!-\!> 0.6) \pm 0.005$
Lateral > 100 μm
(pure)

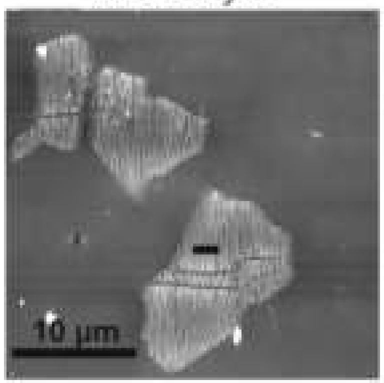
Prof. Josef Breu

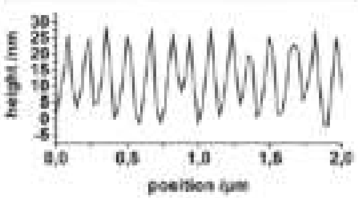
UNIVERSITÄT BAYREUTH

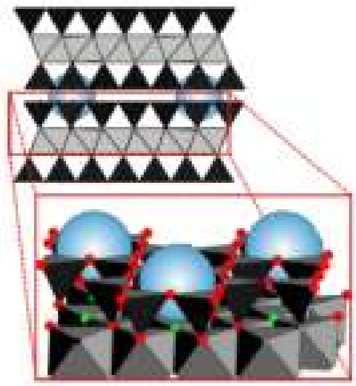
Nanomechanics – Wrinkling

$$E_p = \frac{3E_s\left(1-\nu_p^2\right)}{\left(1-\nu_s^2\right)}\left(\frac{\lambda}{2\pi h}\right)^3$$

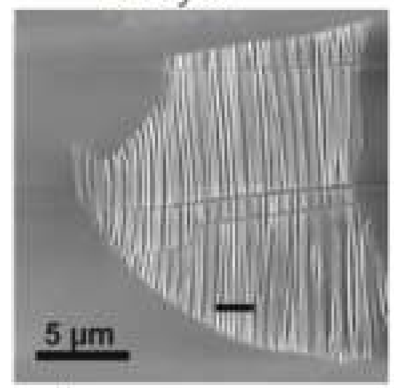
Monolayer

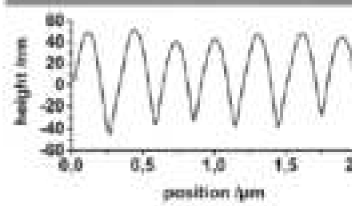






Bilayer

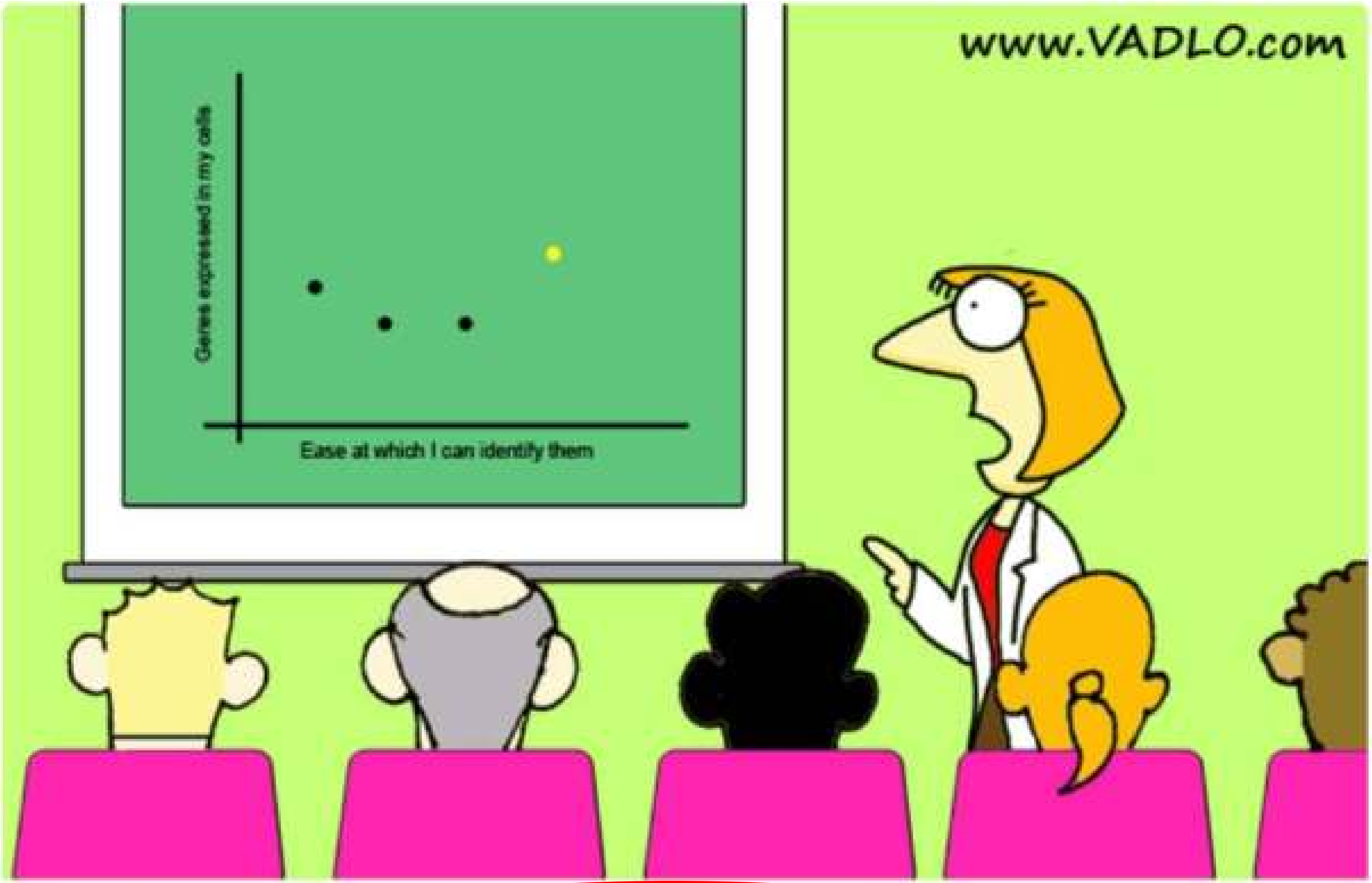




wavelength: 145 ± 7 nm
In-plane modulus: 0.15 ± 0.02 TPa

wavelength: 313 ± 10 nm
In-plane modulus: 0.17 ± 0.01 TPa

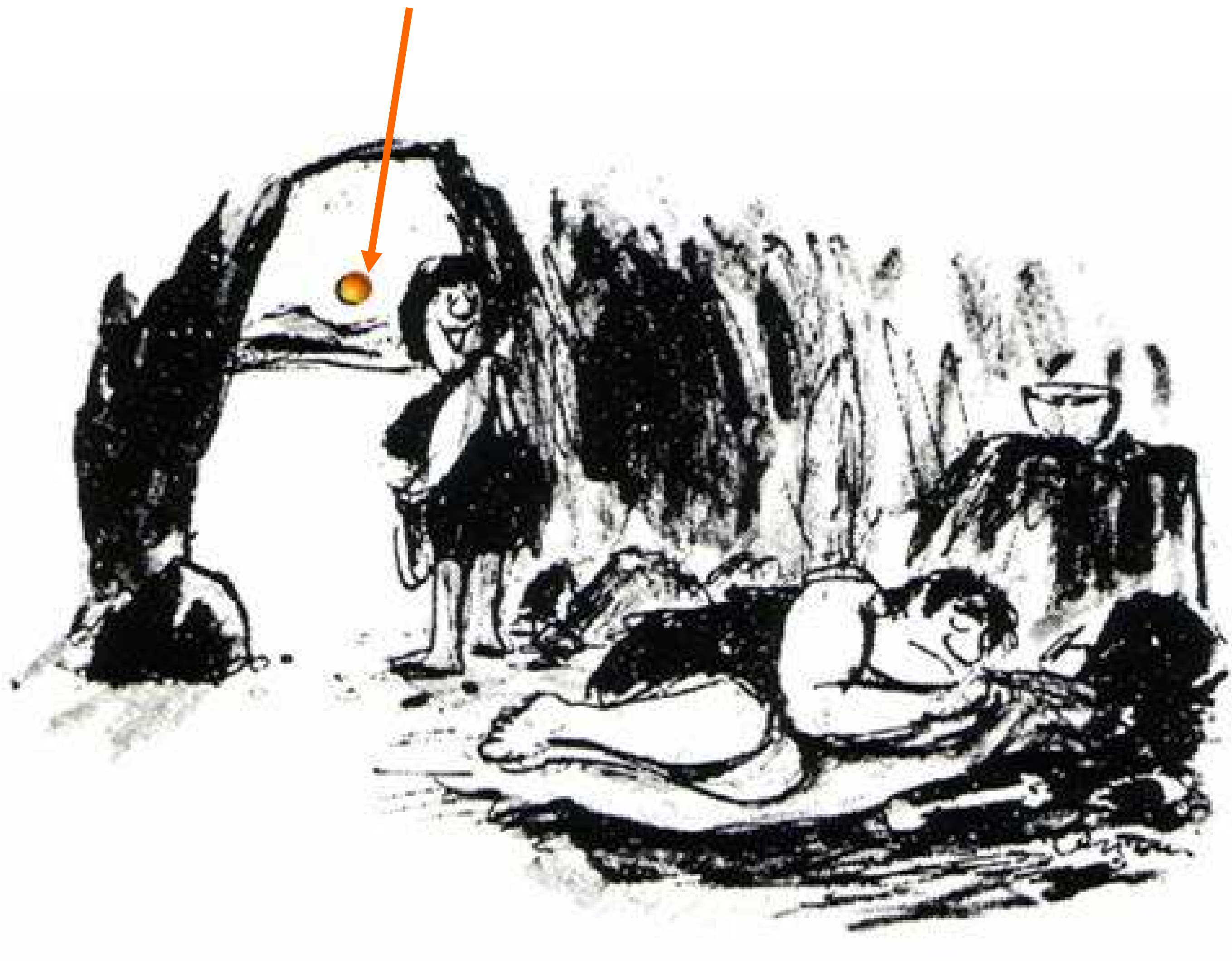
D.A. Kunz et al., *Adv. Mater.* **2013** *25* 1337
D.A. Kunz et al. *ACS Appl.Mat.Interf.* **2013**. 5, 5851.



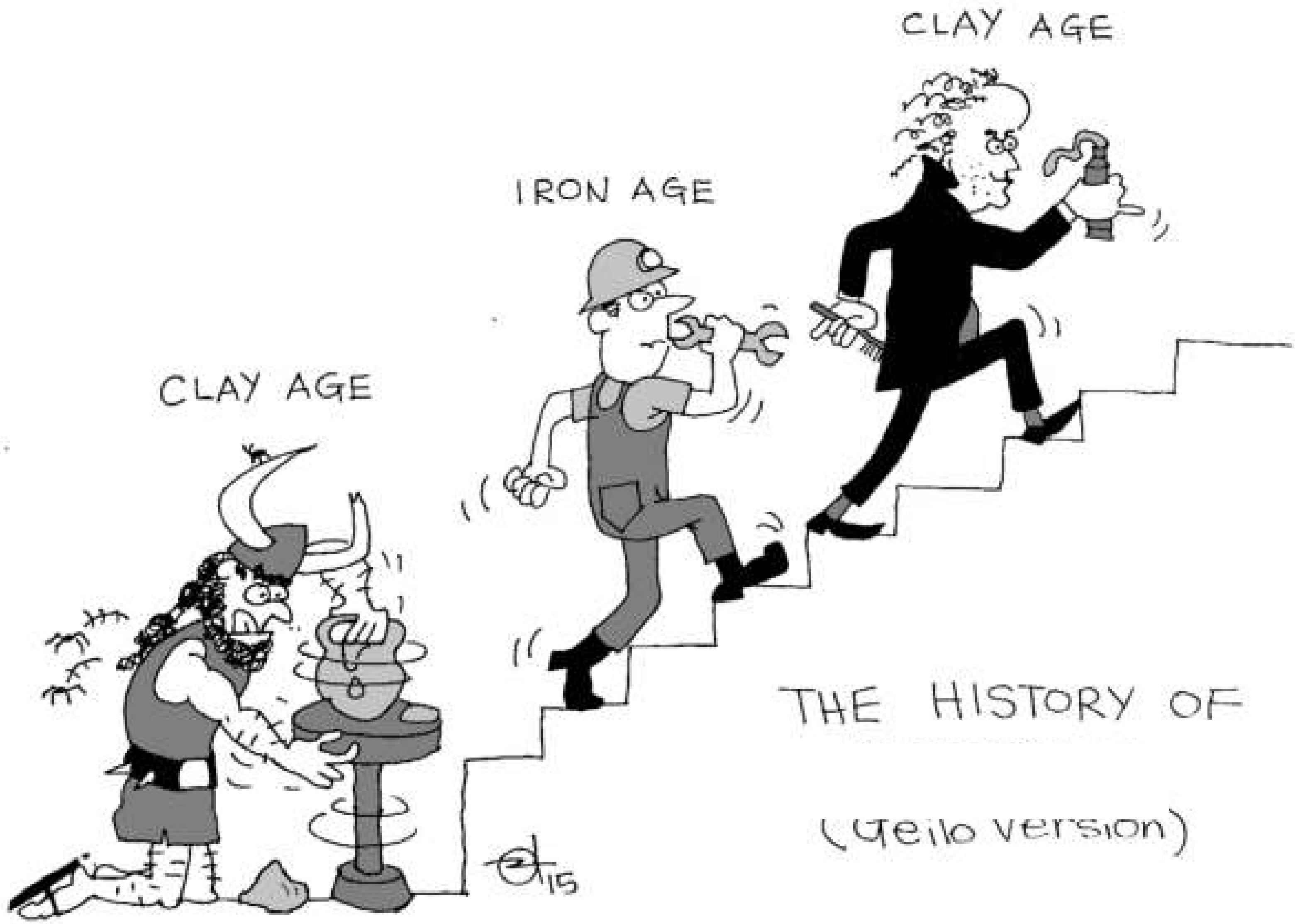
“Same graph as last year,
but now I have an additional dot.”

true for Geilo talks

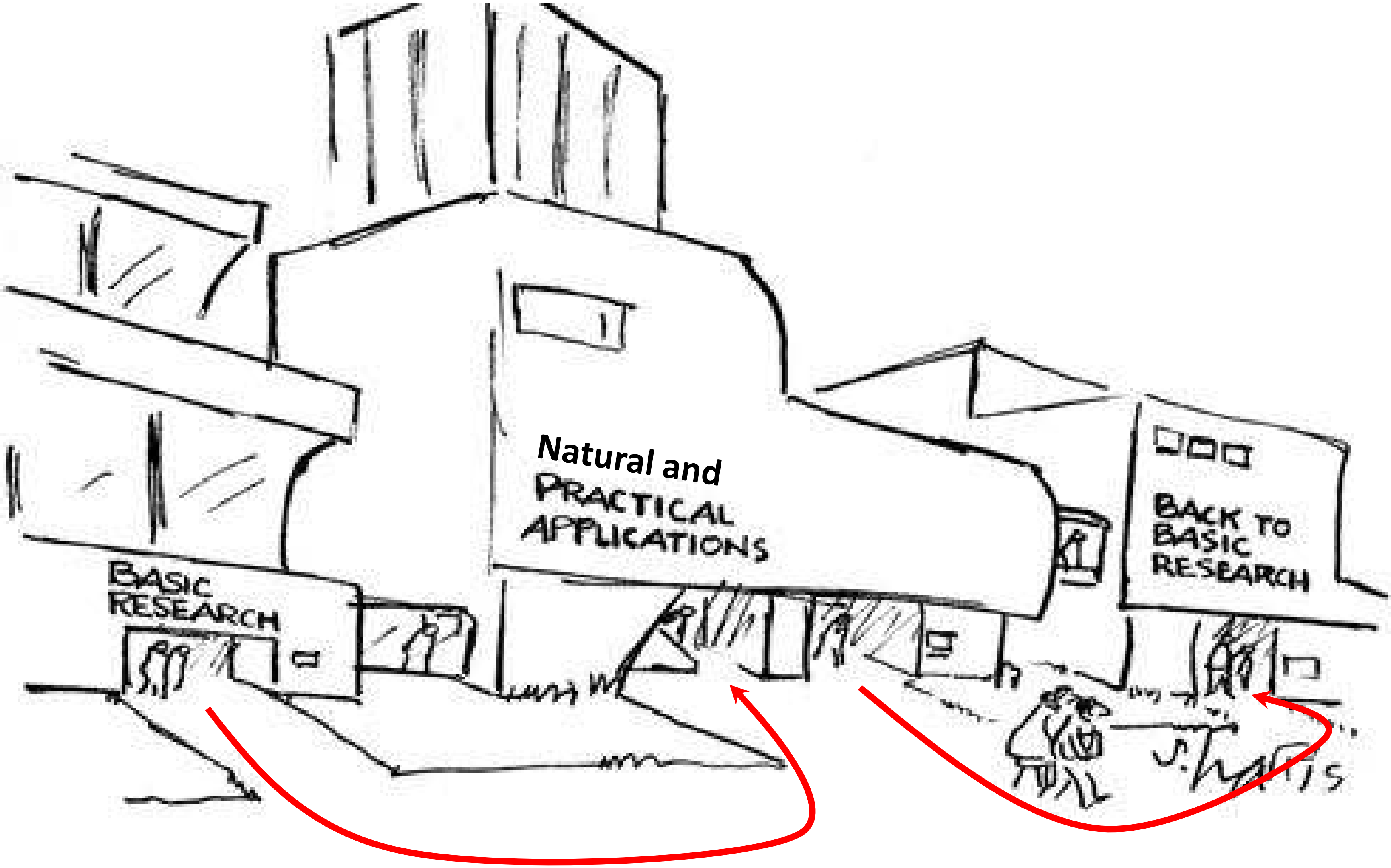
Curiosity driven research



«HEY, SAM, THE BIG ROUND YELLOW THING CAME UP AGAIN»



Drawing by Ernesto Altshuler

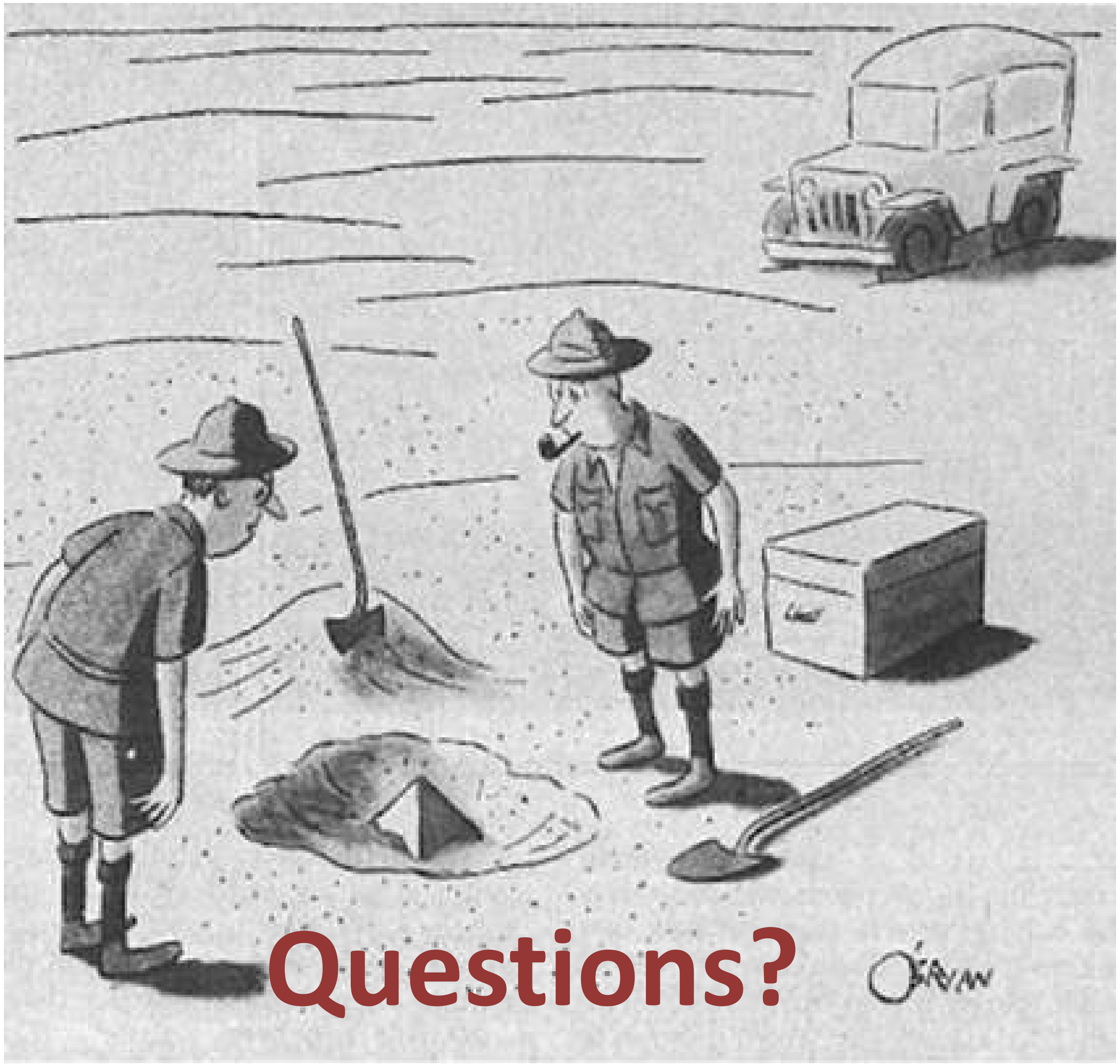

Natural and
PRACTICAL
APPLICATIONS
BASIC
RESEARCH
BACK TO
BASIC
RESEARCH

Acknowledgements to

MSc + PhD students, postdocs,
Collaborators in several countries

Clay baths will prolong your life:

Thank you for your attention!



Questions?

"This could be the discovery of the century. Depending, of course, on how far down it goes."