Where in the World could Life Originate between Mica Sheets?

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Abstract: Mica is so heat resistant that it has been used for stove windows. Therefore mica could be a site for life's origins in hydrothermal vents or any other plausible site for the origin of life, on Earth or even Mars, where biotite mica has been found [1].

Cycles of wetting and drying are a simple feasible way to create prebiotic polymers from monomers such as amino acids [2]. These cycles would have occurred on land but not in hydrothermal vents deep in the ocean. This is an advantage of water on or near land for the origin of life.

Biopolymers are sensitive to heat, which is an argument for origins of life in cooler places than hydrothermal vents. Furthermore, the cells of all organisms have high intracellular potassium (K) ion concentrations, while oceans have high sodium (Na) ion concentrations and low K ion concentrations. These arguments all suggest that life originated in a site cooler and lower in Na ions than hydrothermal vents.

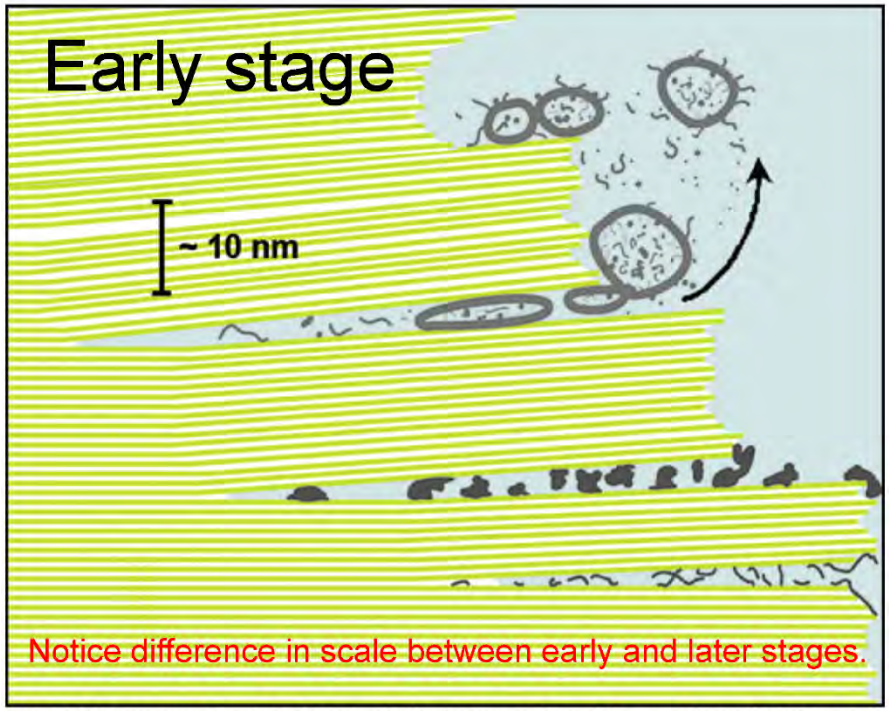
The anionic mineral sheets of Muscovite mica are bridged by K ions. Origins of life between Muscovite mica sheets would explain the high K-ion concentrations found in all living cells. Gradual wetting and drying in the spaces between mica sheets would provide gentle conditions for biopolymer polymerization by wetting and drying, as compared with the extremes of wetting and drying on exposed surfaces. Moving mica sheets also provide an endless source of mechanical energy, for biomolecular syntheses by mechanochemistry, without the need for chemical energy such as ATP and the energy transduction from chemical energy to mechanical energy that typically occurs in living systems [3-6].

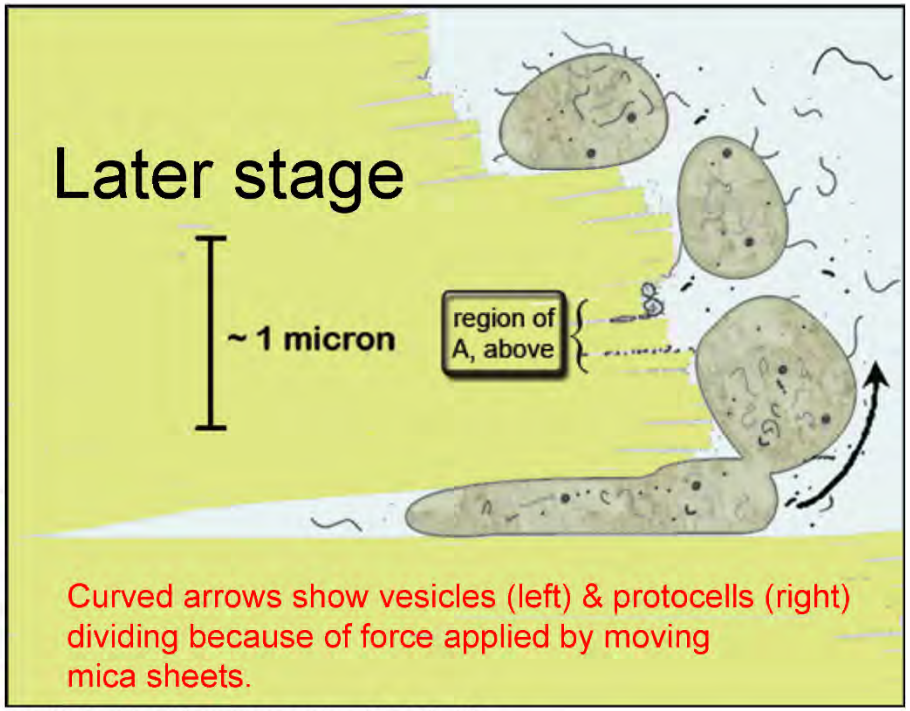
References:

1. Weiss, B.P., et al., *A Low Temperature Transfer of ALH84001 from Mars to Earth.* Science, 2000. **290**(5492): p. 791-795.
2. Lahav, N., D. White, and S. Chang, *Peptide formation in the prebiotic era: thermal condensation of glycine in fluctuating clay environments.* Science, 1978. **201**(4350): p. 67-69.
3. Hansma, H.G., *Could Life Originate between Mica Sheets?: Mechanochemical Biomolecular Synthesis and the Origins of Life*, in *Probing Mechanics at Nanoscale Dimensions*, N. Tamura, et al., Editors. 2009, Materials Research Society: Warrendale, PA. p. II03-15.
4. Hansma, H.G., *Possible origin of life between mica sheets.* Journal of Theoretical Biology, 2010. **266**(1): p. 175-188.
5. Hansma, H.G., *Possible Origin of Life between Mica Sheets: How Life Imitates Mica.* J. Biol. Struct. Dynamics, 2013. **31**(8): p. 888-895.
6. Hansma, H.G., *The Power of Crowding for the Origins of Life.* Origins of Life and Evolution of Biospheres, 2014. **44**(4): p. 307-311.

Mica World

Did life emerge between muscovite mica sheets?





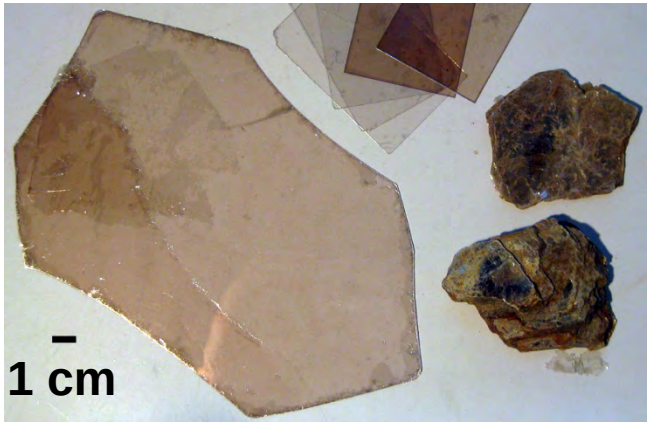
1. H G Hansma, Possible Origin of Life between Mica Sheets: How Life Imitates Mica. 2013. J Biol Struct Dynamics, 31, 888-895.
2. H G Hansma, Possible Origin of Life between Mica Sheets. J Theor Biol 2010. 266, 175-188.
3. Hansma, H. G. 2009. Could Life Originate between Mica Sheets?: Mechanochemical Biomolecular Synthesis and the Origins of Life In: Probing Mechanics at Nanoscale Dimensions. N. Tamura, A. Minor, C. Murray, and L. Friedman, editors. Materials Research Society, Warrendale, PA. II03-15.

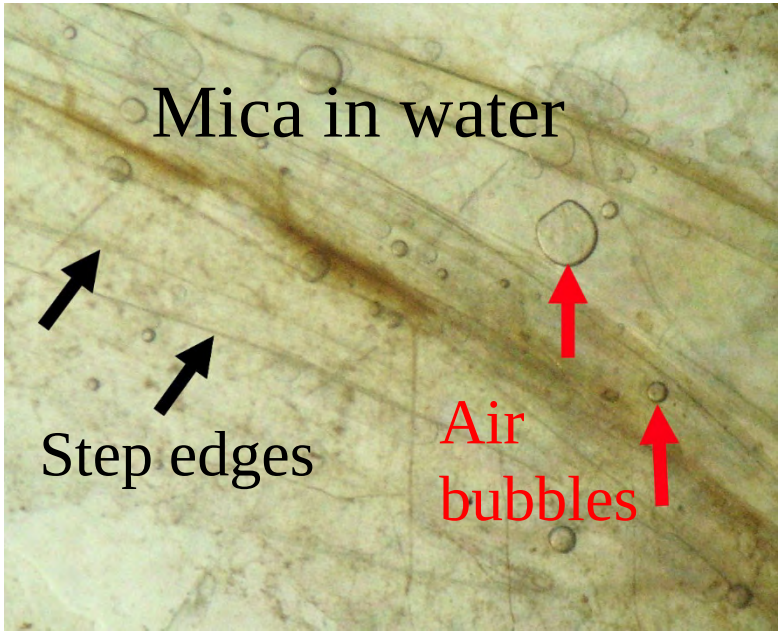
http://web.physics.ucsb.edu/~hhansma/HGHpublications.htm

A Mica World could be the home for an RNA World, Lipid World, Metabolism First or Icy or Hydrothermal Origins.

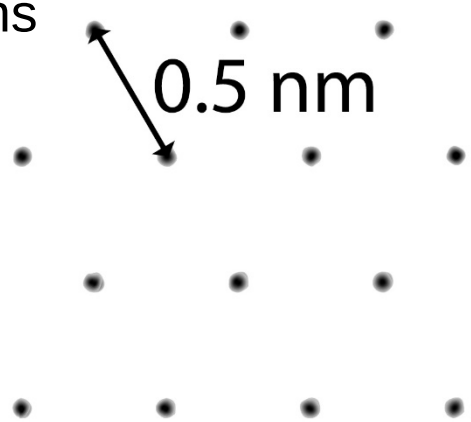
Muscovite mica melts at ~1300 C.

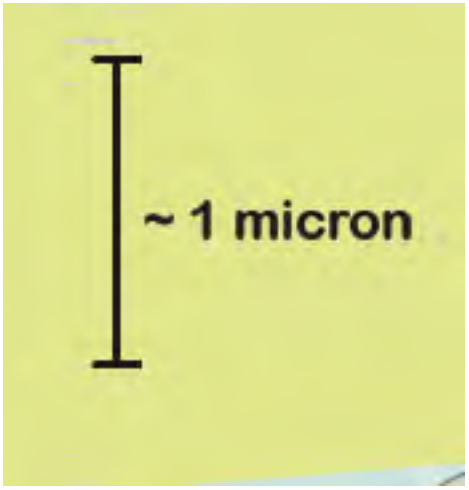
Muscovite Mica – a layered aluminosilicate mineral



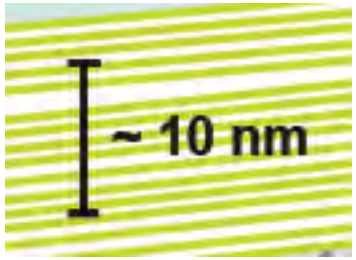


Surfaces of mica sheets have recessed hydroxyl groups with a partial negative charge, bridged by K ions



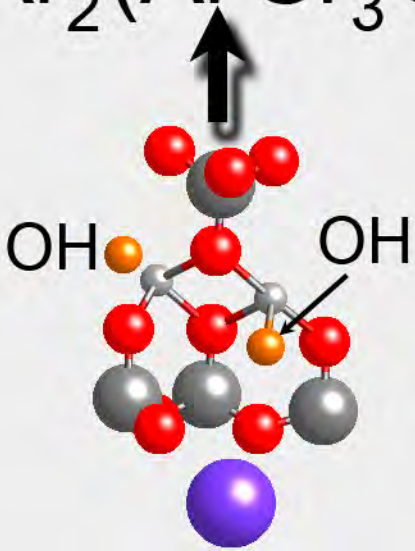


Mica sheets are 1 nm thick

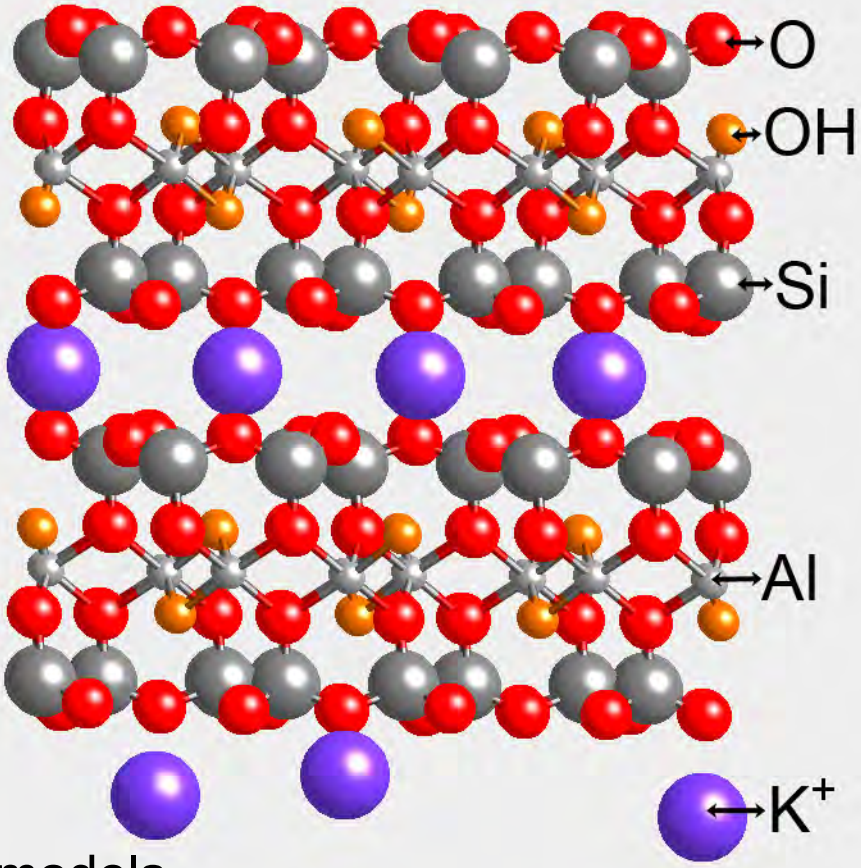


Structure of Muscovite Mica

$K\,Al_2(Al\,Si_3O_{10})(OH)_2$ = Muscovite Mica



Unit Cell

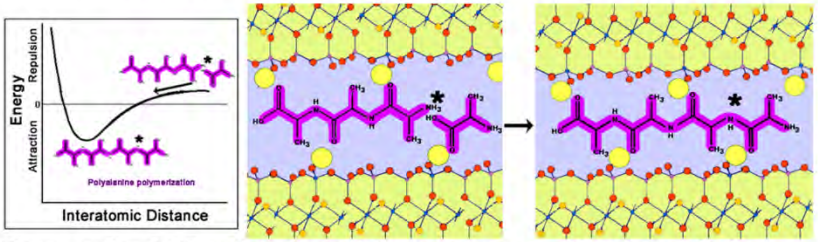


Mica is a non-swelling clay mineral.

CrystalMaker models

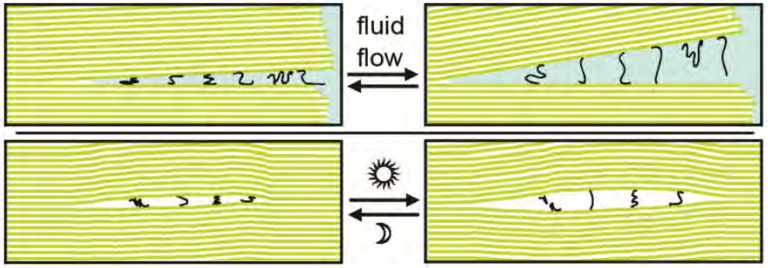
Mechanical Energy (Work) from Moving Mica Sheets can:

1. Form covalent bonds

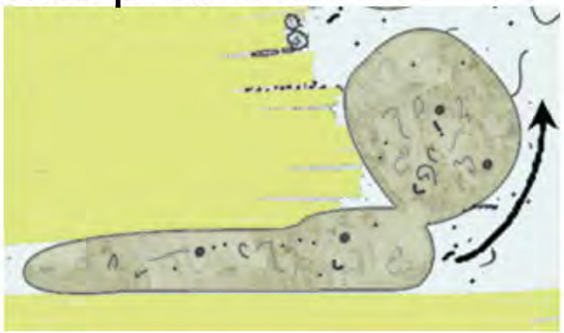


Energetics? Peptide bond free energy of hydrolysis is ~ -2.4 kcal/mole = ~170 pN x 0.1 nm as work for peptide bond synthesis

2. Rearrange polymers



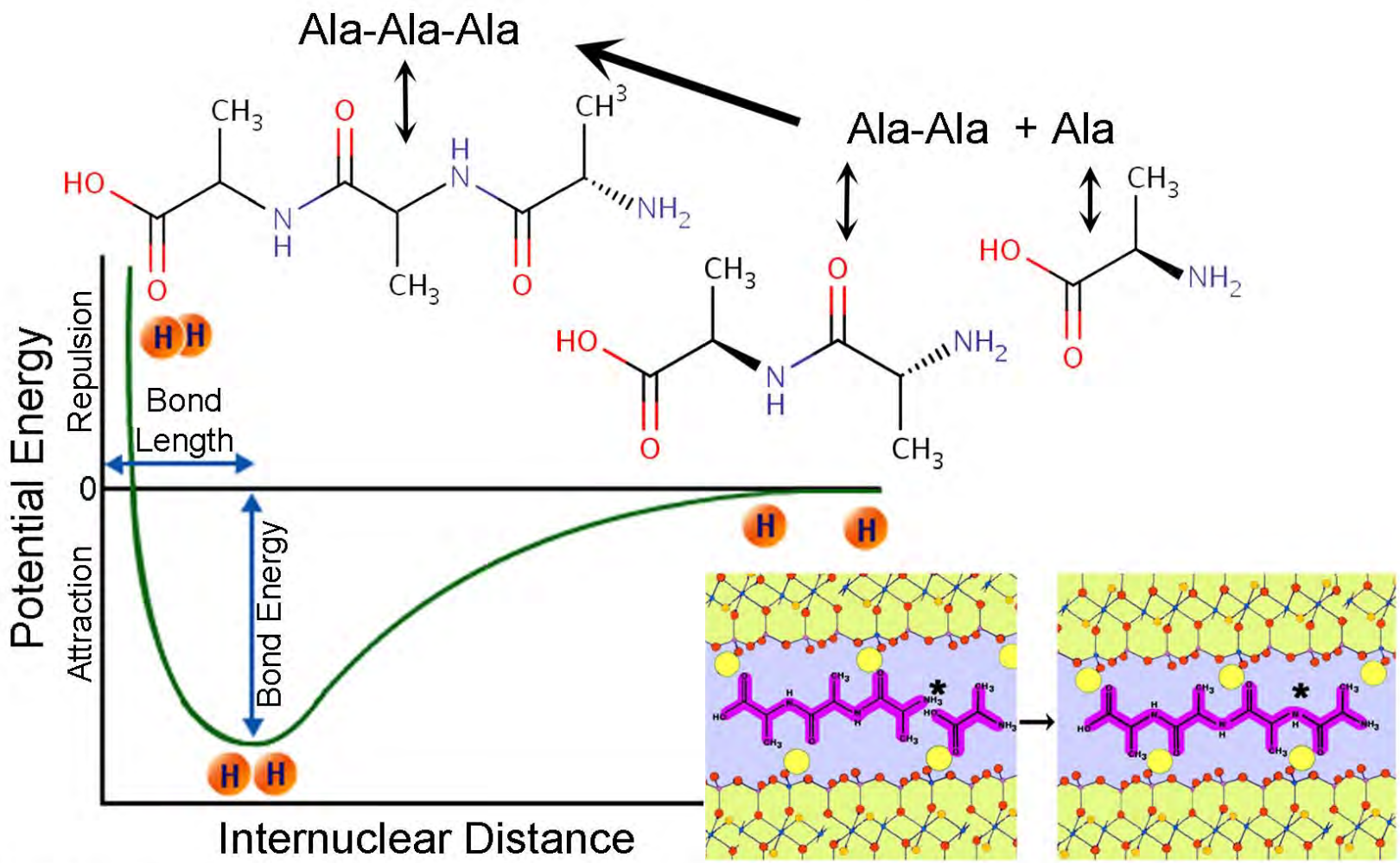
3. Bleb off vesicles ... and protocells



...Like cell division in wall-less L-form bacteria. See HHansma J Theor Biol 2010 & Leaver et al Nature 2009

Was this work a major energy source for the origins of life?

The Ultimate in Crowding - Mechanochemical Synthesis

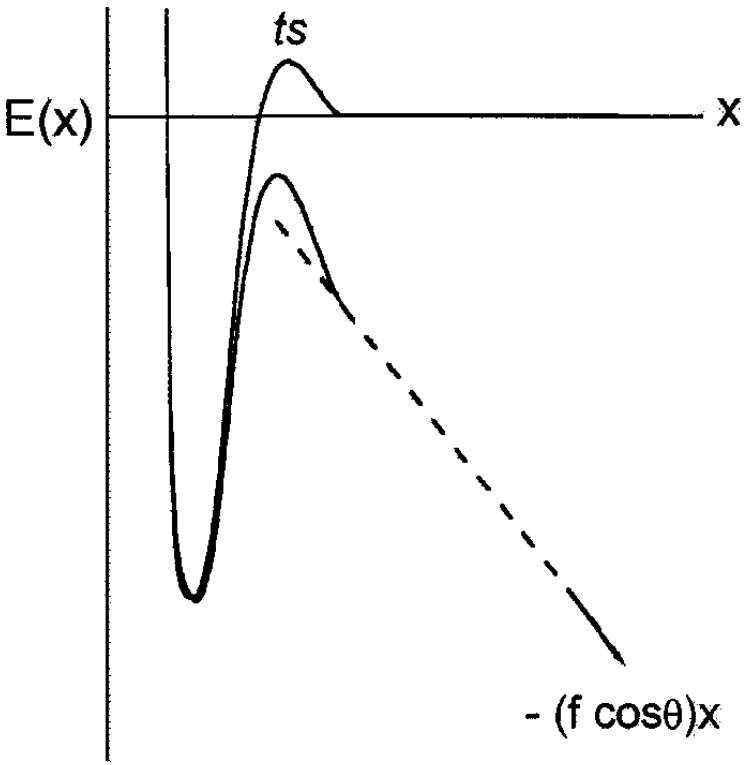


Polyalanine Polymerization by Mechanochemistry?

Mechanochemistry: force lowers transition states (ts) for reactions

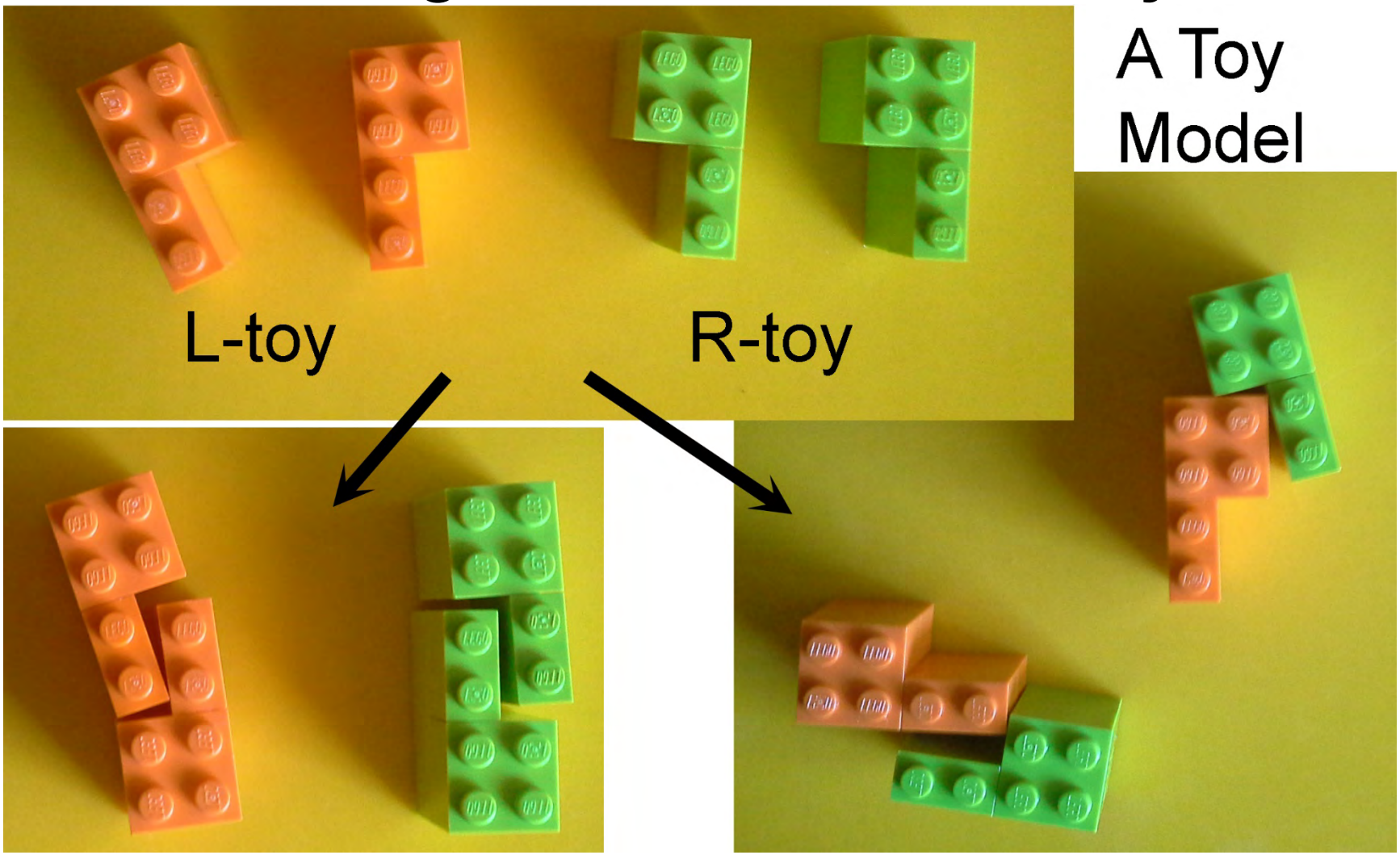
- This is a conceptual energy landscape for a bond with a sharp activation barrier or transition state (ts).

- An external force, f, tilts the landscape and lowers the barrier by adding a mechanical potential, -(f cos θ)x



From Evan Evans, Ann Rev Biophys Biomol Struct 2001. 30:105

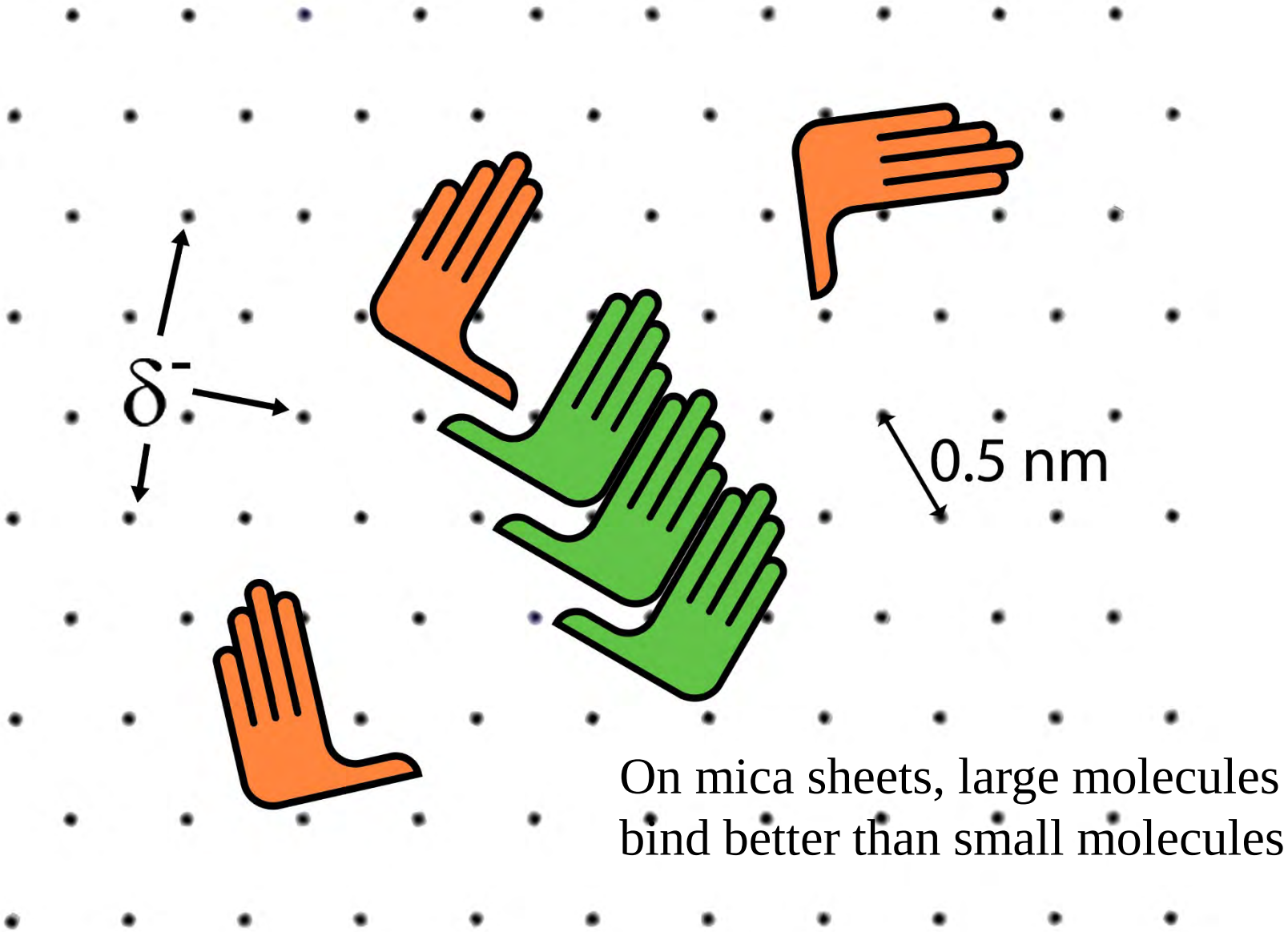
Can crowding lead to Homochirality?



Homochiral dimers are compact

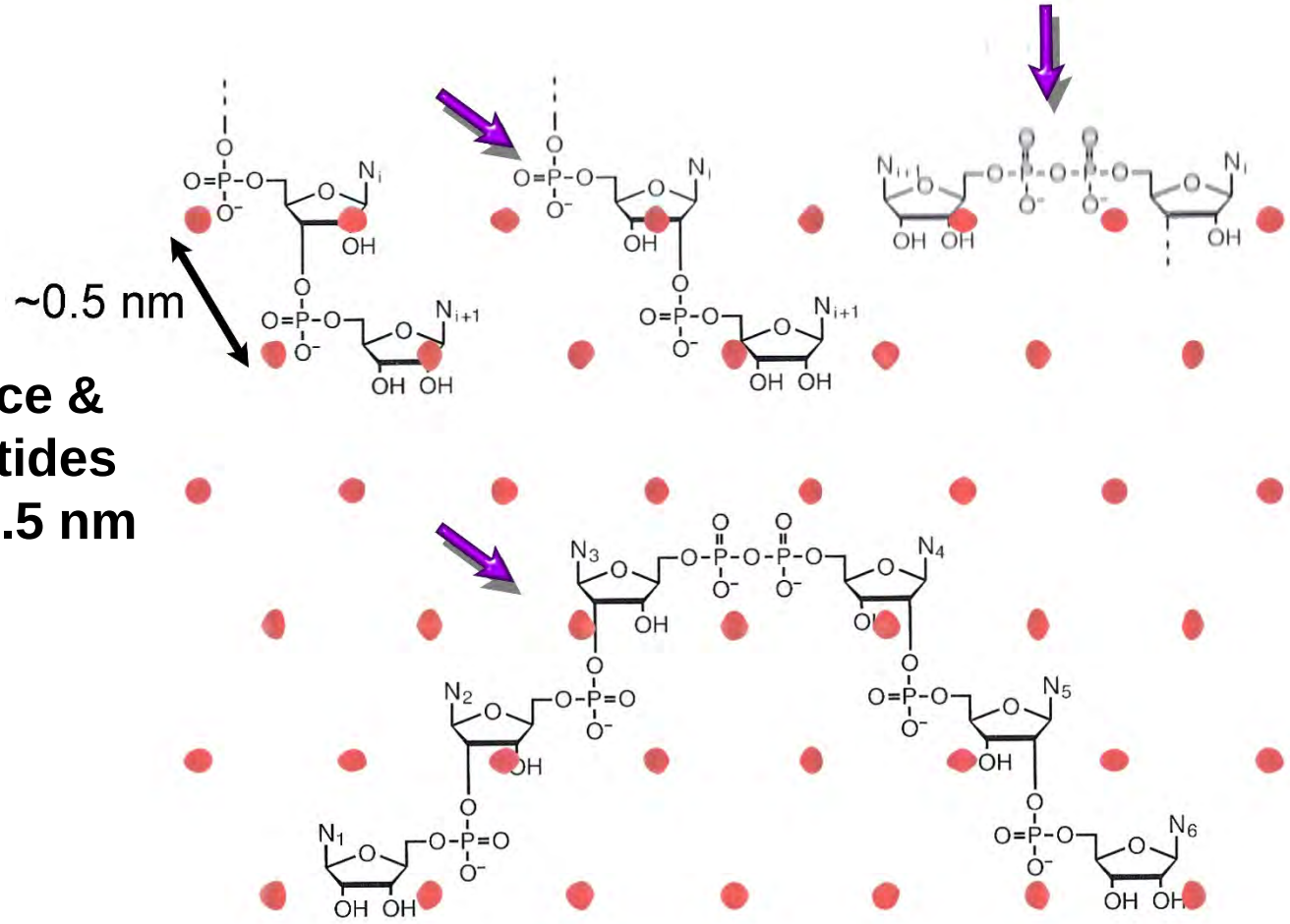
Heterochiral dimers pack poorly

Homochiral Polymerization between 2 Crystalline Sheets?



On mica sheets, large molecules bind better than small molecules

Does this crystal lattice discourage the formation of unnatural nucleotide linkages [purple arrows]?

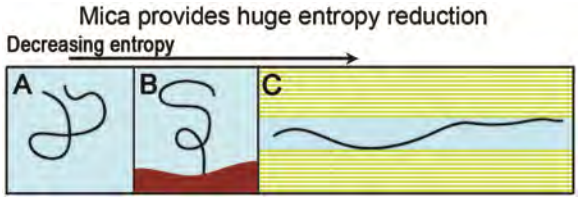


Crystal lattice & 3'-5' nucleotides both have 0.5 nm spacing

Molecules modified from Joyce & Orgel in The RNA World 3rd Ed., Gesteland Cech & Atkins, Eds.

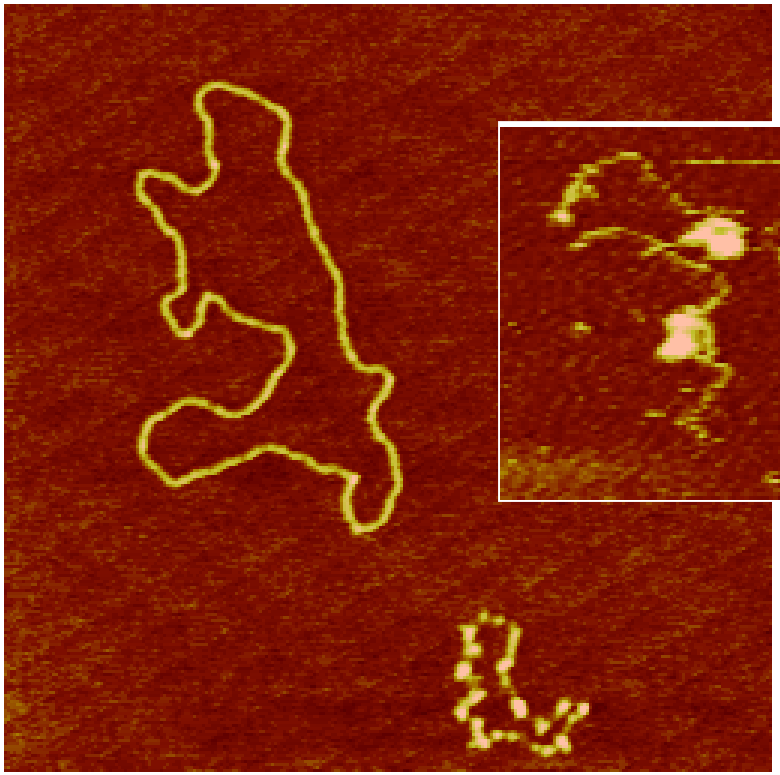
Why Crowding?

- Diffusion distances are shorter for chemical reactions
- Chemistry in confined spaces gives fewer different products
- Life has very few of the possible amino acids, sugars, etc
- Proteins in confined spaces are stabilized against denaturation
- Confinement by pressure induces polymerization of actin and glycine
- Entropy decreases with confinement
- Molecules in cells are crowded
- Life was hard to ‘make’ – don’t make it harder!



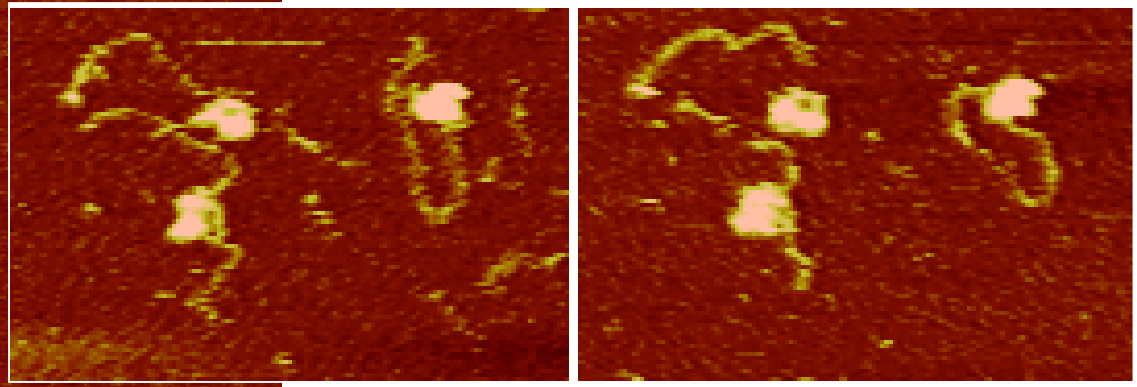
See HHansma 2010 J Theor Biol 2010 and the references therein.

Biomolecules adsorb to mica



DNA on mica in atomic force microscope

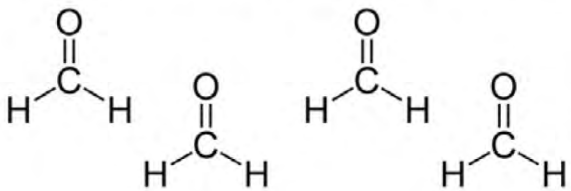
‘Swimming’ DNA



- Ni^{2+}, Co^{2+} & Zn^{2+} hold DNA on mica under fluid.
- George Cody said yesterday those are best for αKG synthesis.

Mica World is Just Right?

1. Formaldehyde doesn't polymerize into tar



hypothetically...

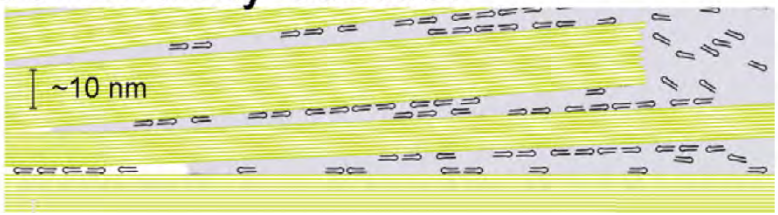
1. The confined confined spaces between the crystalline surfaces of mica sheets are likely to favor smaller and simpler sugars than would form on surfaces or in solution

2. There are (almost)
   No deserts
   and
   No floods

2. Water content between mica sheets changes only gradually, as in the water-mica sandwich. Amino acids polymerize when dried, but too much water hydrolyzes polymerrs

3. Isolation is needed for RNAs to evolve without being wiped out by the most 'successful' ribozymes.* Community is needed for RNAs with different functions to combine, to create a sufficiently large 'genome'

3. Both Isolation & Community coexist

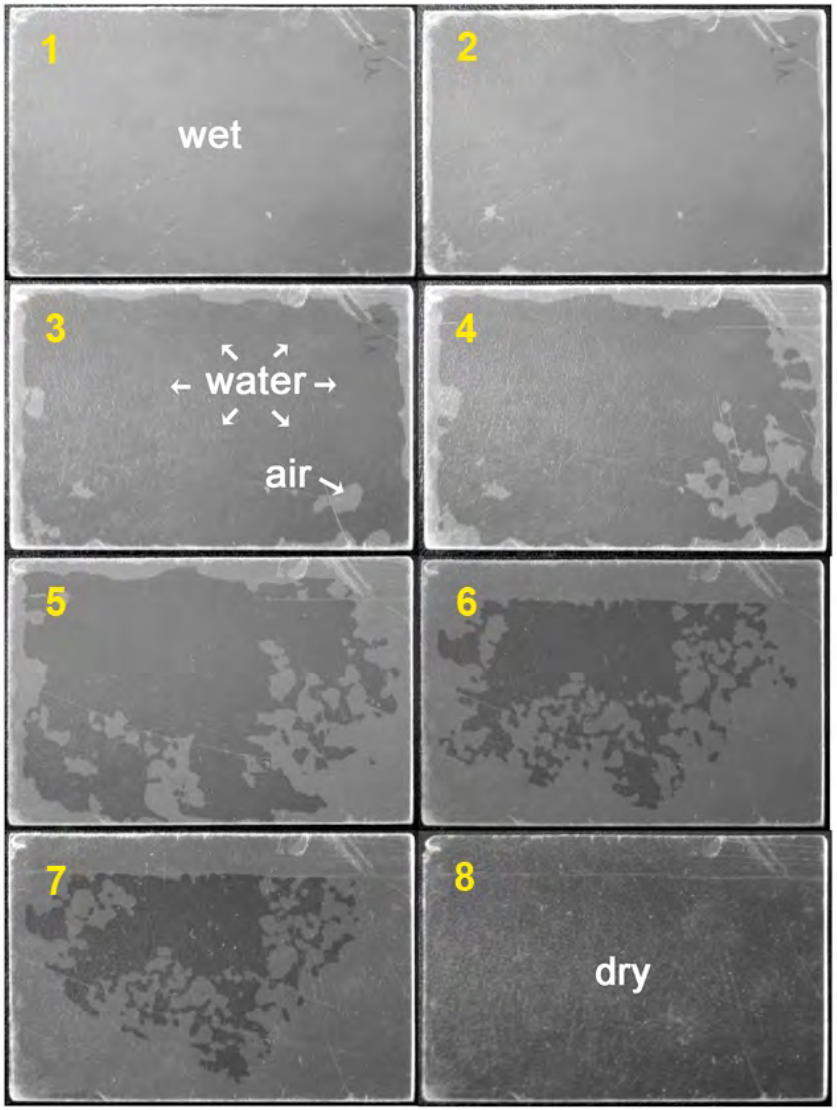


Mica has vast spaces between its sheets (= isolation) and edges where molecules such as RNAs can meet and join up (= community)

See Woese PNAS 25 June 2002 for a communal or ecosystem view of life's origins

*Szabo *Nature* 21 Nov 2002.

Mica water sandwiches were photographed at intervals from 0 to 24 hrs:



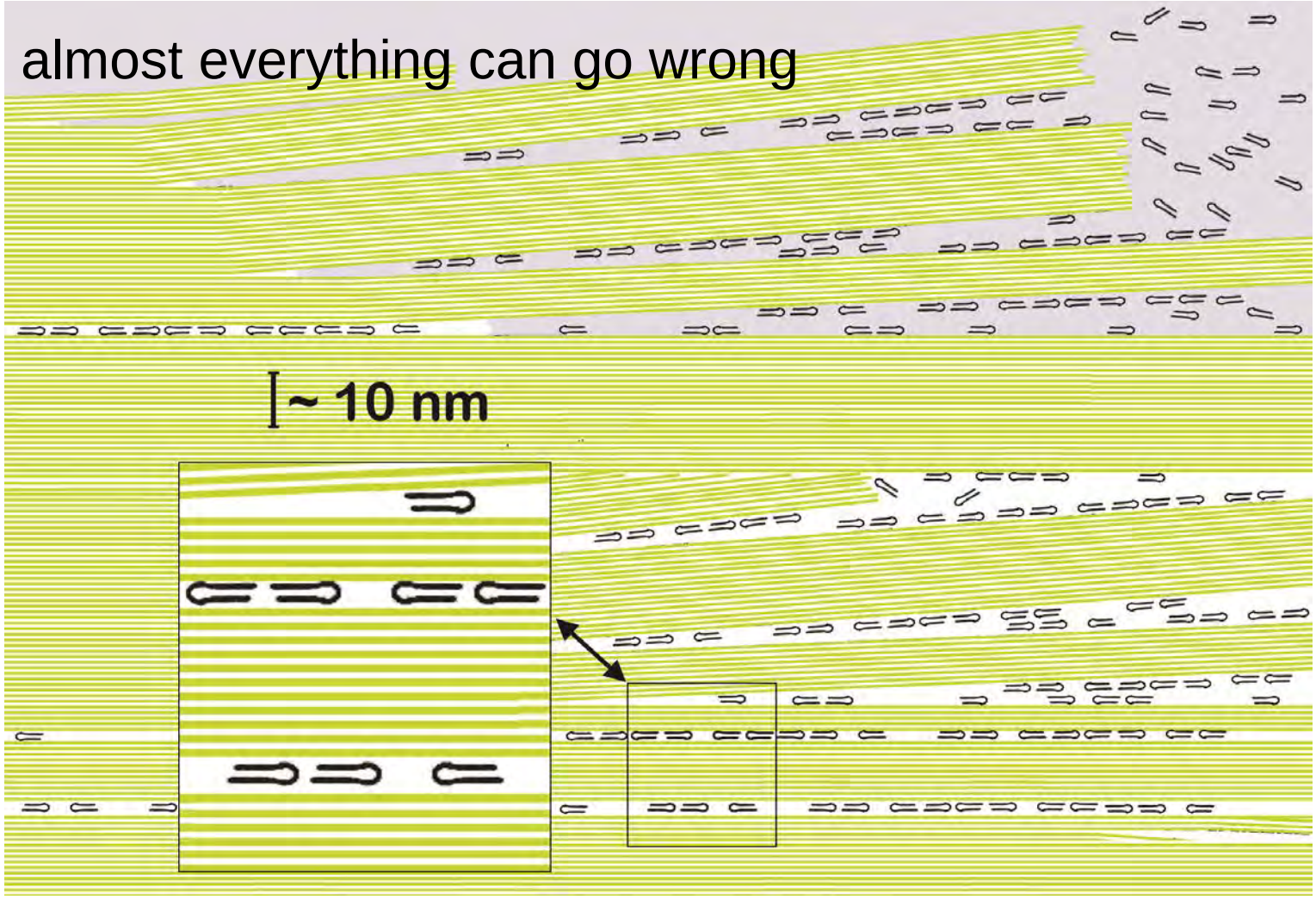
Mica sheets provide controlled wetting & drying

Problems with swelling clays or exposed surfaces:

Too Wet - Biopolymers hydrolyze in water

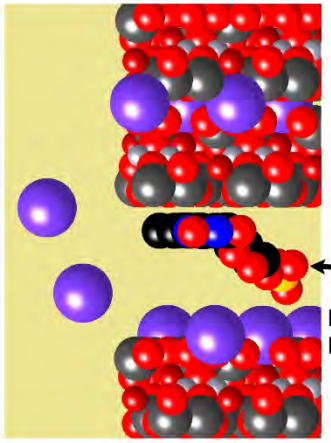
Too Dry - Amino acids polymerize when dried, but life needs water

Mica provides massive redundancy –

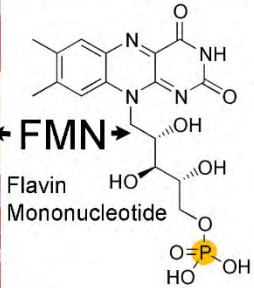


Error tolerance is the main requirement for the origin of life –
Freeman Dyson

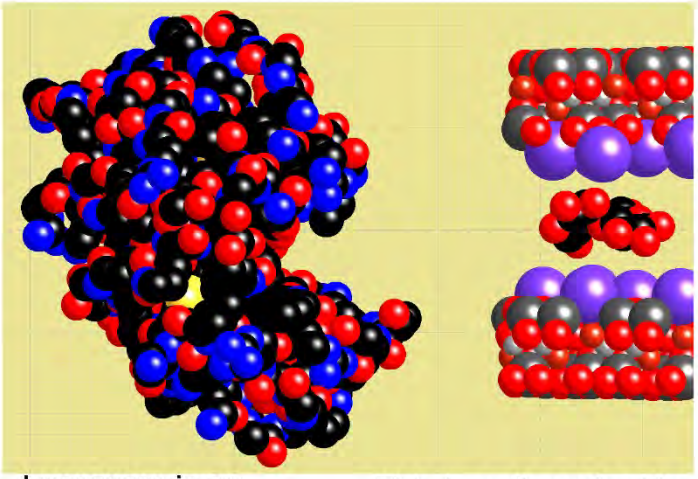
Are these characteristics of life artifacts of their origins between mica sheets?



Did Enzyme-cofactor complexes evolve from cofactor-mineral sandwiches such as this?

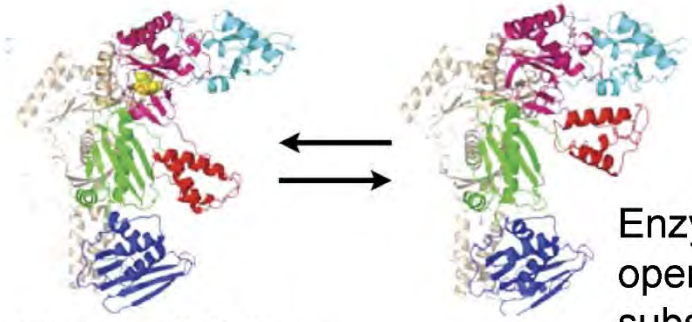


Are moving mica sheets the precursors of enzymes?



Lysozyme is an enzyme that degrades polysaccharides

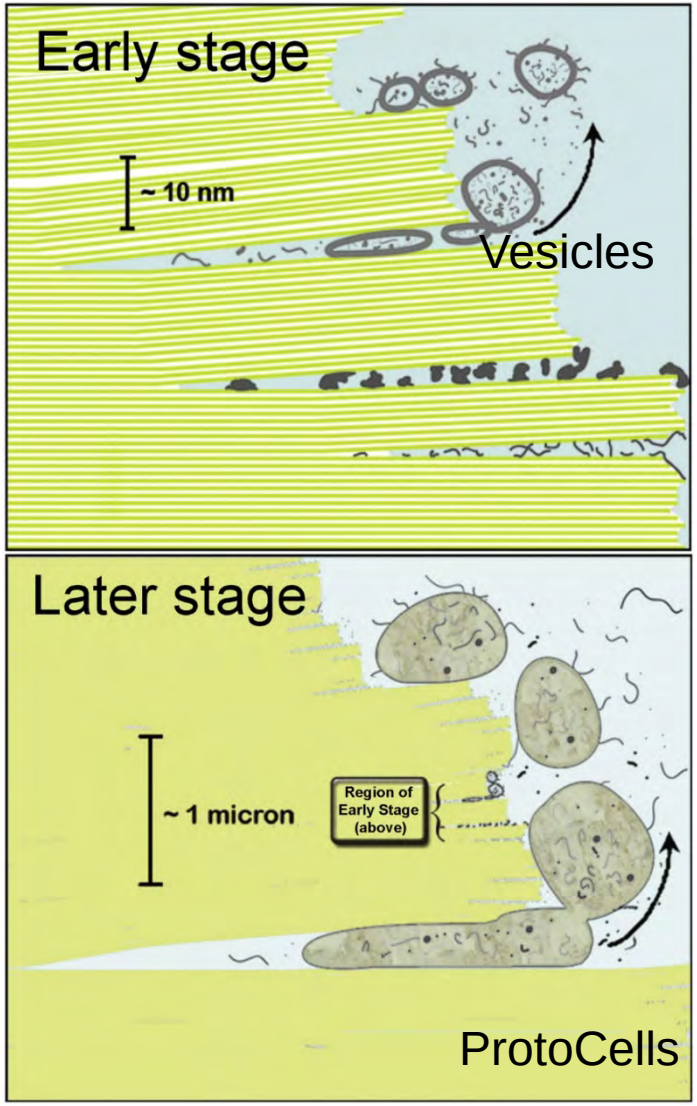
This is a disaccharide, maltose, between mica sheets.



Enzyme is HIV-1 RT
Bahar et al, Curr Opin Struct Biol 2007

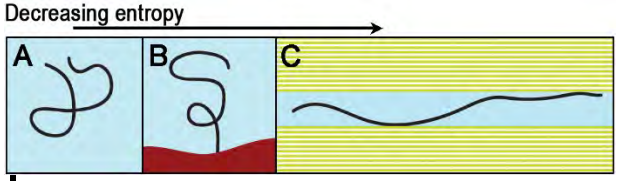
Enzymes spontaneously fluctuate between open and shut conformations whether or not substrates or cofactors are present.
Is this due to the origins of life between mica sheets?

Mica World



Muscovite Mica provides:

- Enclosure
- Both Isolation & Community
- Good Wet / Dry balance
- Work for **Mechanochemistry**
- Chemical confinement effects
- Solid state synthesis
- **K^+** between mica sheets - & in our cells
- Low entropy



- High error tolerance
- **Structured water** at mica surfaces
- 0.5-nm crystal lattice = spacing of bases in extended ssRNA.

Summary

- **Membraneless organelles:** they bring RNA and protein together now – and at life's origins?

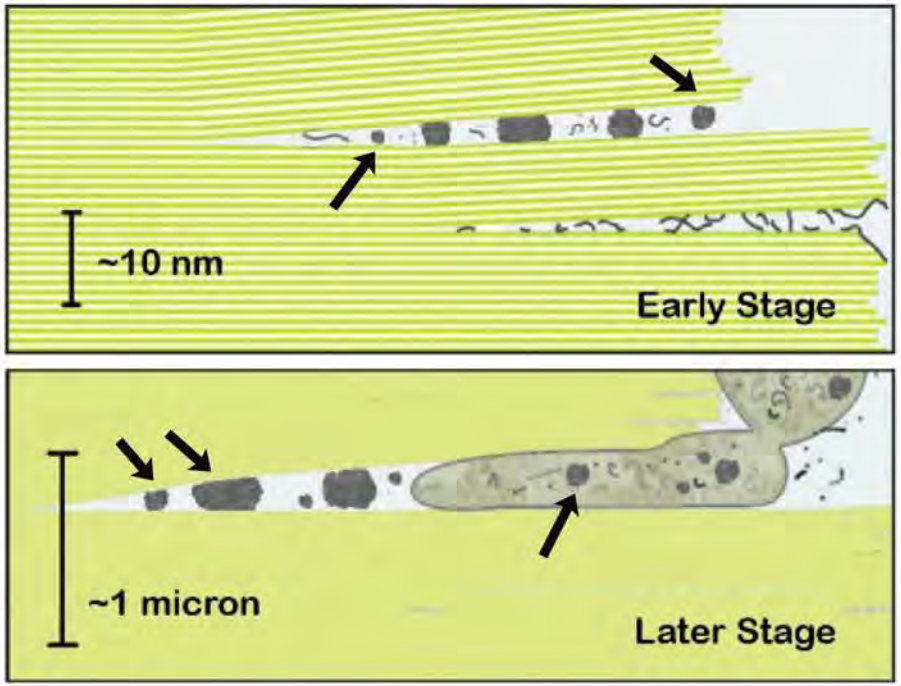
- **Between [Muscovite] Mica sheets:** a good place for life's origins – "Cells" before Membranes?

- **Mechanical Energy:** ubiquitous in living systems – and essential for life's origins?

http://web.physics.ucsb.edu/~hhansma/mica.htm

Cells before Membranes:

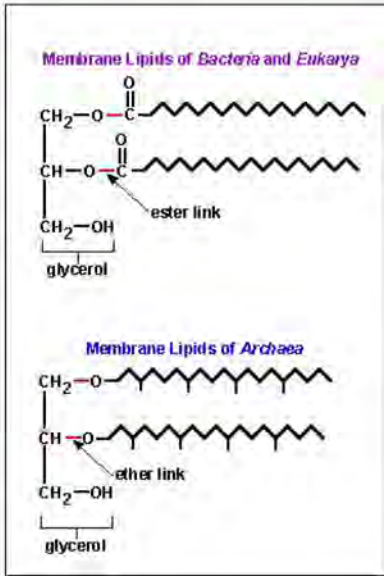
Organelles without Membranes between Mica Sheets?



Problems with Membranes at the Origins of Life:

1. **Membrane properties:**
   - Fragility
   - Sensitivity to ionic strength
   - Tendency to lose and acquire molecules
   - Likelihood of being too impermeable or too leaky

Multi-layer membranes at the origins of life would minimize most of these problems.

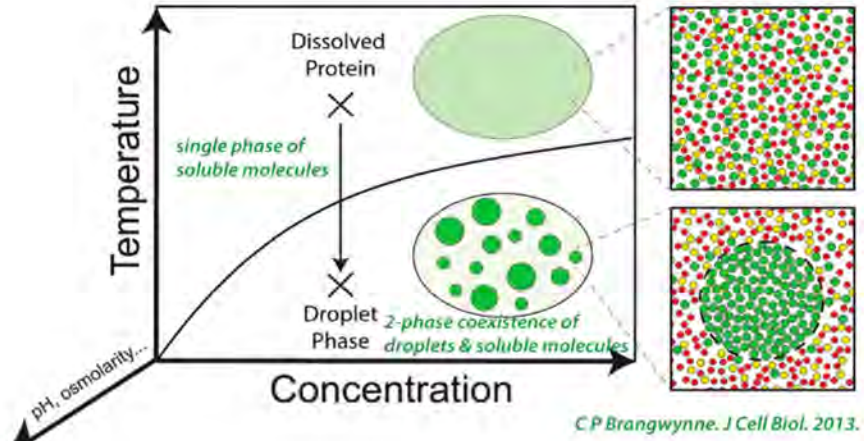


2. **Living cells have 2 types of membrane lipids:**
   - Ester-linked lipids in Eukaryotes and Bacteria
   - Ether-linked lipids in Archaea

This is a problem for 'Membranes First' origins.

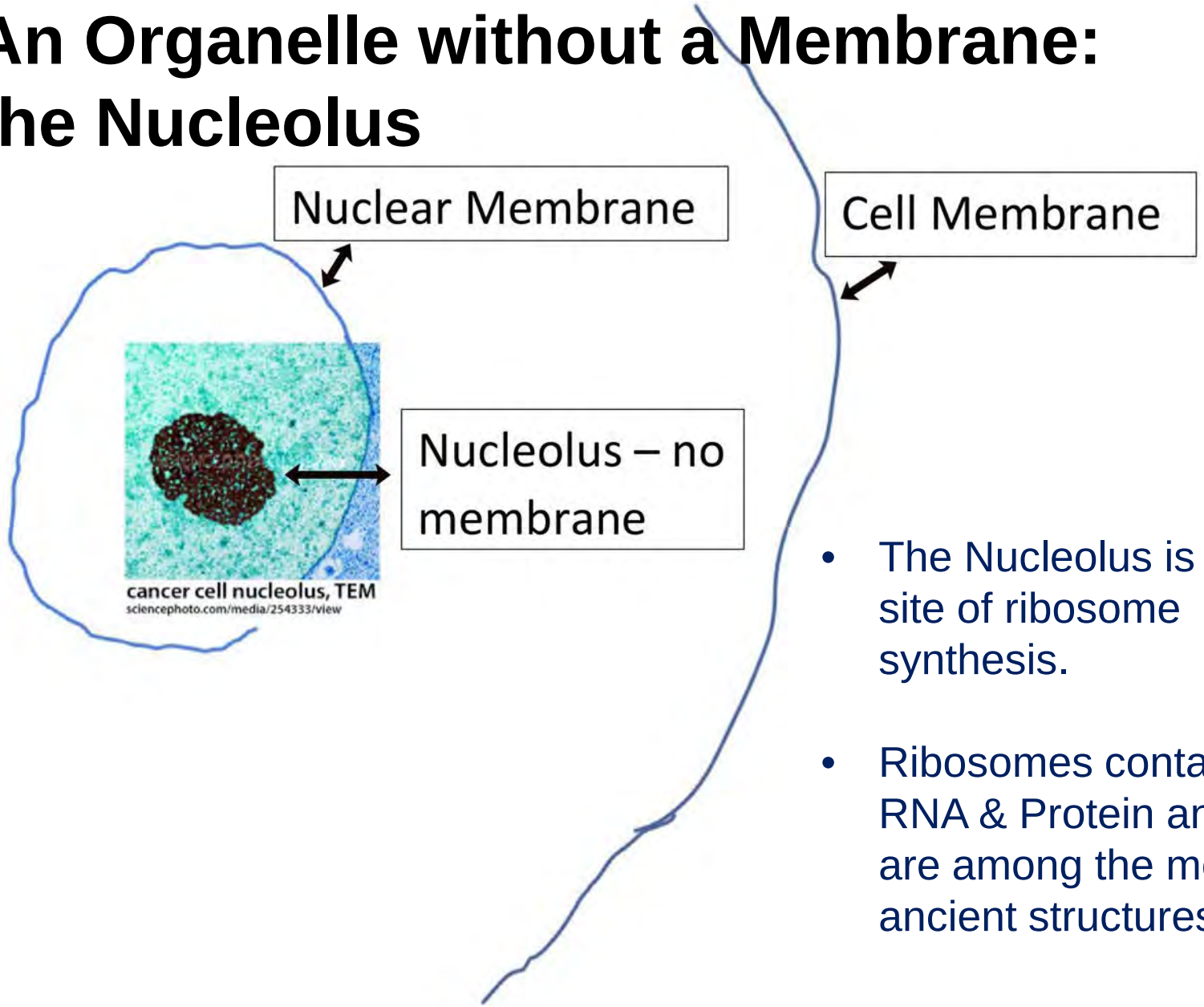
Organelles without Membranes:

- Form spontaneously by liquid-liquid phase separation
- Contain RNA and protein
- Are found in Eukaryotes, Bacteria & Archaea
- Crowding & force fluctuations facilitate their formation



The Proteins are RNA-binding, Low Sequence Complexity, with Intrinsically Disordered Regions, likely to be found at the origins of life. The proteins melt double-stranded DNA.

An Organelle without a Membrane: the Nucleolus



- The Nucleolus is the site of ribosome synthesis.
- Ribosomes contain RNA & Protein and are among the most ancient structures.

- **If RNA and proteins now self-assemble into nucleoli and other organelles without membranes, did they start doing this at life's origins?**
- Proto-ribosomes might have formed this way.
- Spaces between mica sheets would have provided a protected environment where this happened.
- An Origin of Life without membranes has been suggested before: Koonin, E.V. and W. Martin, ***On the origin of genomes and cells within inorganic compartments.*** TRENDS in Genetics, 2005. **21**(12): p. 647-654.