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Tidal chain reaction (TCR) and the origin of replicating biopolymers

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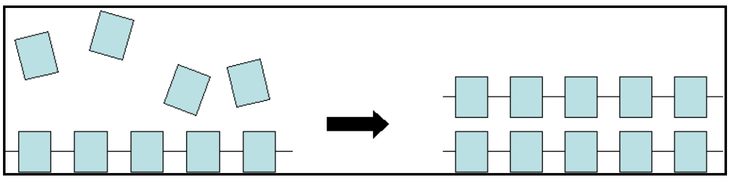
Abstract. Template-directed polymer assembly is a likely feature of prebiotic chemistry, but product blocks further synthesis, preventing amplification and Darwinian selection. Nucleic acids are unusual because charge repulsion between opposing phosphates permits salt-dependent association and dissociation. It was postulated that tides at ocean shores provided the driving force for amplification: evaporative concentration promoted association / assembly on drying, while charge repulsion on tidal dilution drove dissociation (1). This permits exponential amplification by a process termed tidal chain reaction (TCR)(2). The suggestion that the prebiotic ocean was hyper-saline places constraints on TCR, but the process is not strictly contingent upon tidal ebb and flow: circadian dews and rainfalls can produce identical cycling. Polymer scavenging, chain assembly by recruitment of pre-formed fragments, is proposed as an alternative to de novo precursor polymerization, with the suggestion that Darwinian selection may have operated on families of related polymers rather than on individual molecules.

SLIDE 1. THE PREBIOTIC SOUP - IN VITRO POLYMERIZATION

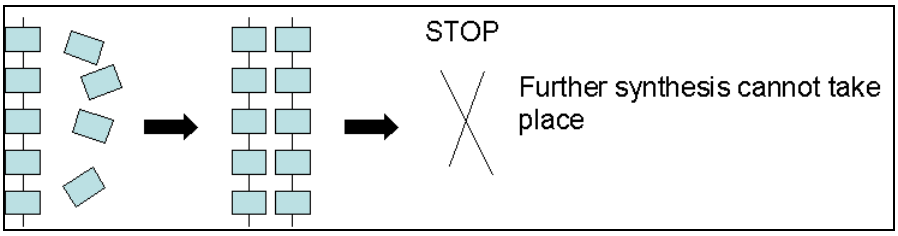
Amino acids → polypeptides

Nucleotides → polynucleotides



Fox and Harada, 1958; Schramm et al., 1962; Naylor and Gillam, 1996; Von Kiedrowski et al., 1989; Ferris et al., 1996; Li and Nicolaou, 2002; Luther et al., 1998

SLIDE 2. TEMPLATE-DIRECTED POLYMERIZATION IS A DEAD-END



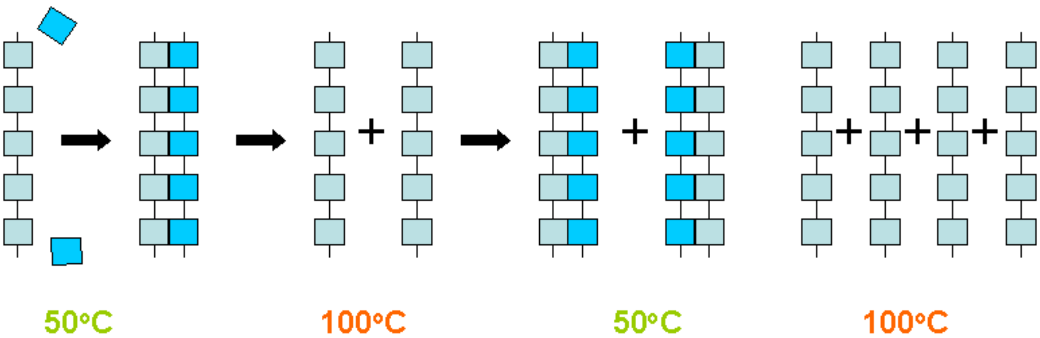
"Somewhere in this cycle work must be done, which means that free energy must be expended. If the parts assemble themselves on a template spontaneously, work has to be done to take the replica off; or, if the replica comes off the template of its own accord, work must be done to put the parts on in the first place"

Harold Blum (1957)

SLIDE 3. TWO QUESTIONS.

- What was the driving force for replication?
- Why nucleic acid?

SLIDE 4. PHYSICAL CYCLING: POLYMERASE CHAIN REACTION (PCR)



Early earth: No evidence for substantial marine temperature cycling

What could drive association / dissociation?

SLIDE 5. FORMATION OF THE MOON IN A SINGLE GIANT IMPACT.

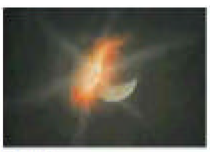


Figure 5
A Giant Collision created the Moon: half an hour after impact.

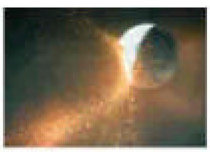


Figure 6
Five hours after the Giant Collision.

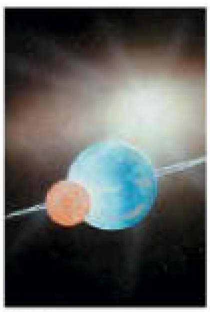


Figure 7
1000 Years after the Collision.

Paintings by William K Hartmann

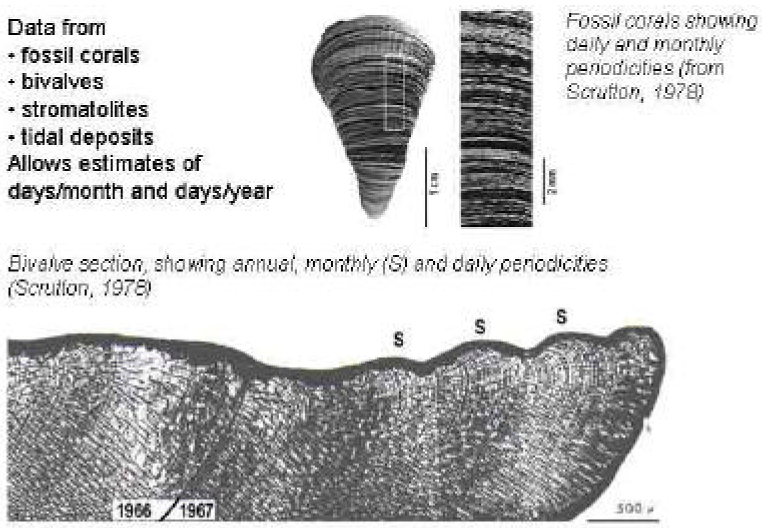
SLIDE 6. FORMATION OF THE MOON

An unusual event

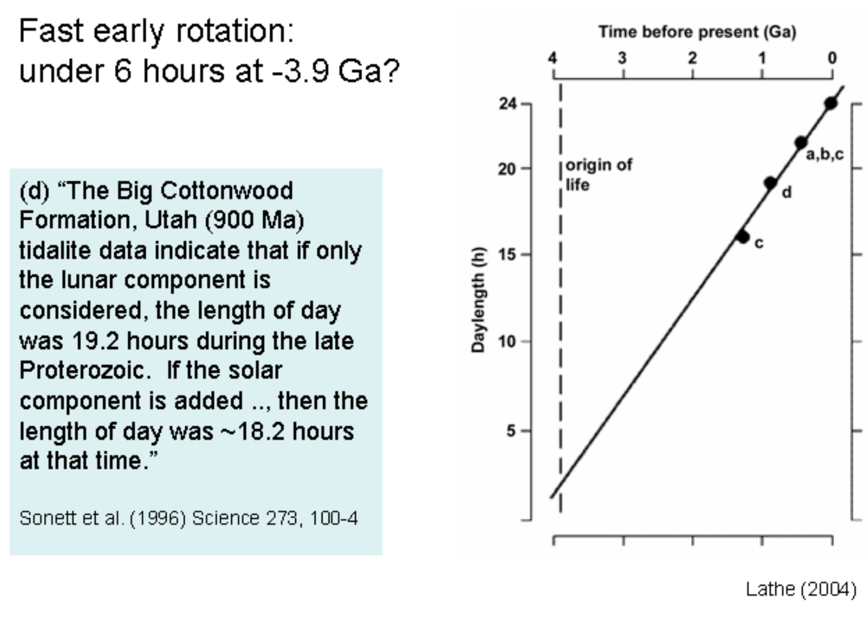
Mass / angular momentum of the event were conserved

Retaining the earth-moon pair in stable orbit

SLIDE 7. FOSSIL EVIDENCE FOR THE RATE OF EARLY ROTATION



SLIDE 8. SPEED OF EARLY ROTATION

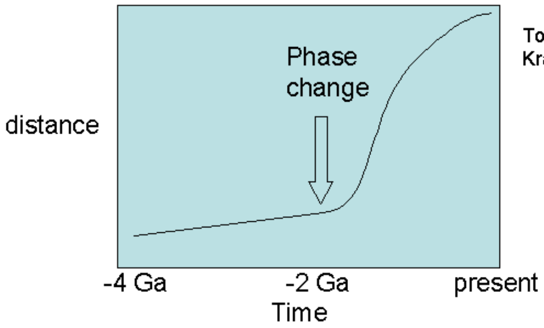


SLIDE 9. GEOBIOLOGICAL AND REGRESSION DATA ARE CONTRADICTORY

- Geological and biological evidence firmly points to surface water and stable terrestrial evolution for the last 4 Ga.

- **“The pace of tidal evolution for the past 450 Myr implies an Earth-Moon collision some 1,500-2000 MyrBP, an event for which there is no corroborating evidence” (Walker and Zahnle, 1986).**

- **Two phase decline of the Earth-Moon pair?**



Touma & Wisdom, 1998;
Krasinsky, 2002

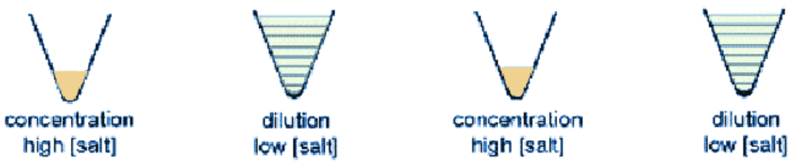
SLIDE 10. RAPID AND EXTENSIVE TIDAL FLOODING AND DILUTION

Ocean temperature 50-100oC

Low [NaCl] concentration

Could tidal cycling have driven replication?

- drying and dilution
- changes in salt and precursor concentrations



SLIDE 11. TWO RULES FOR THE ‘ORIGIN OF LIFE’

Origin of life defined as primitive biopolymer replication

1. **First: Polymerization during the drying phase**

- Precursor concentrations were limiting: maximum concentrations during drying
- Partially anhydric conditions favor chemical reactivity (bond formation through dehydration)

2. **Second: Dissociation during the dilution phase**

- If polymerization takes place during drying, dissociation must take place on dilution

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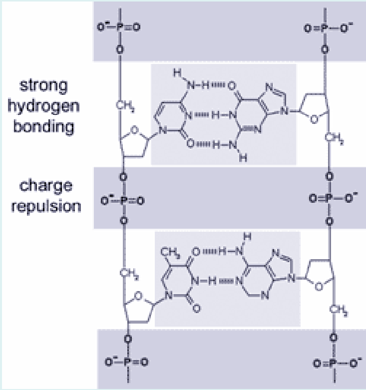
SLIDE 12. NUCLEIC ACIDS - INVERTED DISSOCIATION /ASSOCIATION VERSUS SALINITY

Most biological polymers associate in low [NaCl] and dissociate in high.

DNA has the reverse behavior.



SLIDE 13. SCHILDKRAUT-LIFSON (1965) RELATION

<u>Melting temperature = 16.6 Log M + 0.41(%G+C) + 81.5 [- 820 / *l*]</u>

M = [NaCl] molarity

G+C = % composition in G/C (usually ~ 0%)

l = length of duplex

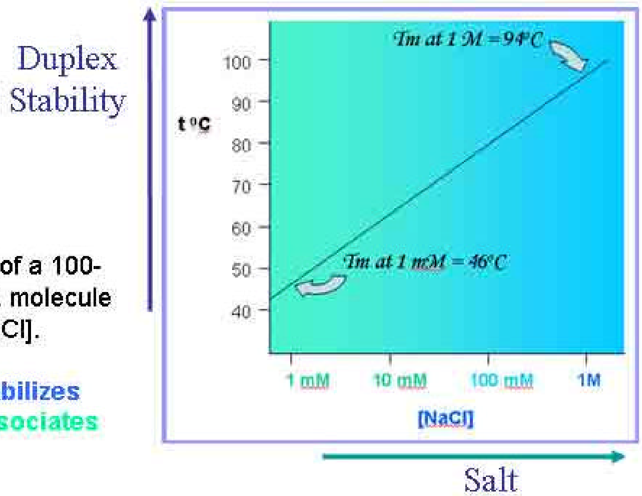


Figure: Melting of a 100-mer duplex DNA molecule according to [NaCl].

High salt → stabilizes
Low salt → dissociates

SLIDE 14. ANIMATIONS

DNA animations

SLIDE 15. TIDAL CHAIN REACTION

PCR – amplification by cycling between high and low temperature

low temperature – template-directed polymer assembly
high temperature – dissociation

TCR – amplification by cycling between high and low salt

high salt – polymer assembly

low salt – dissociation

SLIDE 16. EARLY CONDITIONS WOULD HAVE PERMITTED ASSOCIATION / DISSOCIATION

Origin of life took place not long after condensation of the oceans

Temperature: **? 50 oC to 100 oC**

Salt: *Supersaline or nearly freshwater??*

(present concentration: **460 mM**)

SLIDE 17. THE SALT PROBLEM

Conventional view
Volatiles (chlorine, sodium) outgassed early
Sequestration could not take place before continent formation (-2.5 Ga)
Early ocean must have been super-saline (0.5 M)
Paul Knauth, pers. comm. Knauth (2005) in press.

Alternative view
High chemical reactivity of outgassed volatiles
Rapid deposition of solid-phase chlorides
Only commenced dissolution on ocean condensation (?-4 Ga)
Early ocean would have been nearly fresh (20 mM)

Which is right?

0.5 M NaCl would prevent dissociation of DNA-like duplexes

SLIDE 18. WHAT IF THE OCEAN WAS SUPER-SALINE?

1. **Dews and rainfalls (land-based)**

Nightime precipitation
Daytime evaporation

2. **Freshwater tides (estuaries)**

Flood-ebb cycles affect river levels for 100s of km inland
(far inland tidal ranges of 4 m in the St Lawrence)

In the Bay of Fundy, salinities vary from marine to fresh in a single tidal cycle

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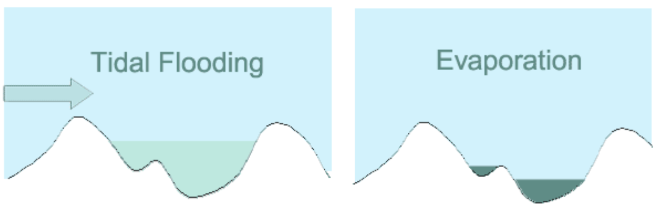
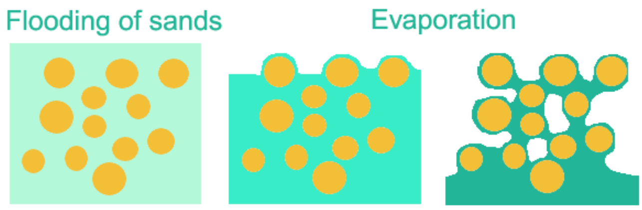
SLIDE 19. MACRO- OR MICRO-SCALE?



scale = metres

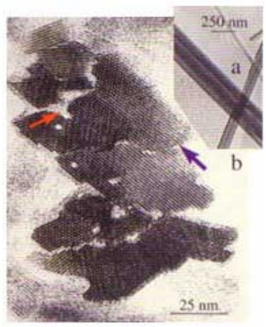


scale = millimetres

SLIDE 20. **FORMATION OF FIRST POLYMERS**

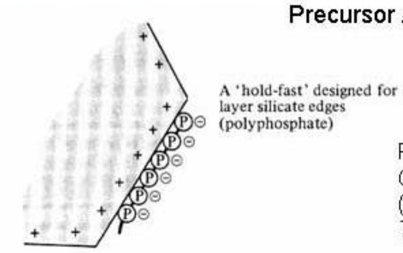
Polymer scavenging

SLIDE 21. MINERAL SURFACES CAN FACILITATE POLYMERISATION



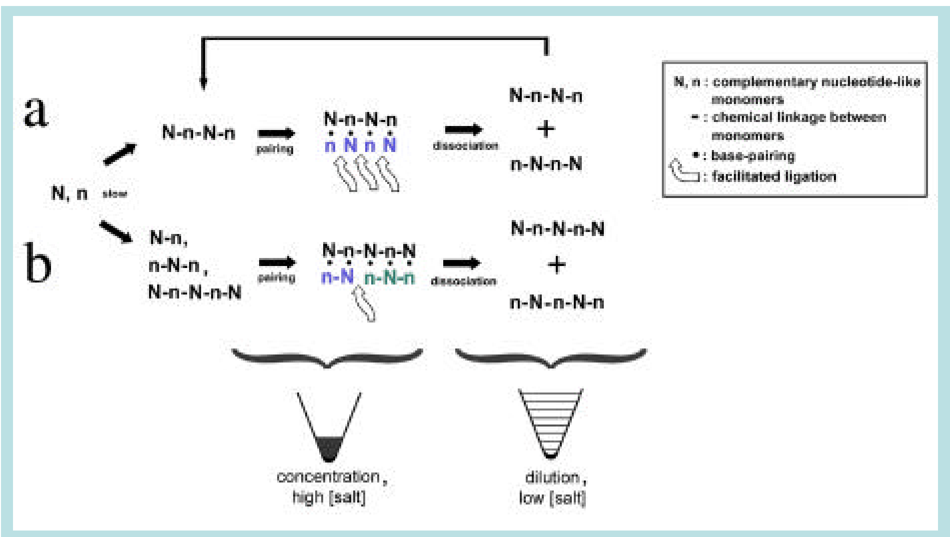
Crystal of sepiolite showing repetitive ridges

Precursor / polymer alignment

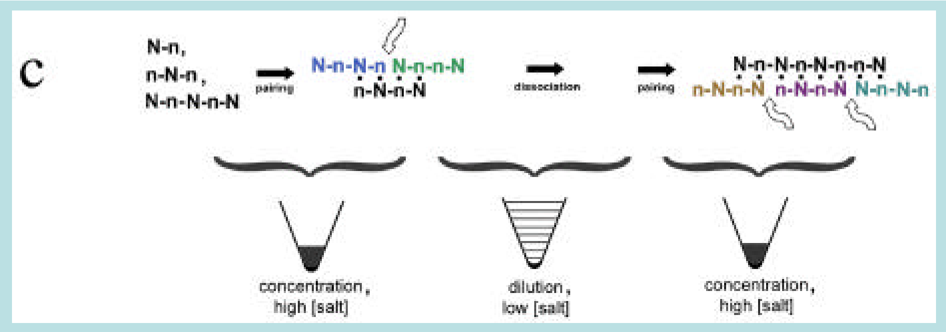


From: **A.G. Cairns-Smith**
Genetic takeover and the mineral origins of life (1982)
The Origin of Life: Clays (2001)

SLIDE 22. TIDAL CYCLING PREDICTS AN EXPONENTIAL INCREASE IN NUMBER



SLIDE 23. .. AND A PROGRESSIVE INCREASE IN CHAIN LENGTH



SLIDE 24. A CENTRAL CAVEAT

Were precursors sufficiently abundant to permit replication of nucleic acids?

- It has been argued that prebiotic conditions may not have permitted the accumulation of critical ingredients, examples: ribose, adenine, uracil **

- The chemistry of cyclic drying has not been fully explored

****see Shapiro (1999) PNAS 96, 4396-4401**

SLIDE 25. SUMMARY AND PERSPECTIVE

A driving force is required for association / dissociation

Rapid early terrestrial rotation (2-6 hours daylength) with a large close moon provides cyclic drying and dilution

2 Rules for the origin of life

- **Association and polymerization during the drying / concentration phase**
- **Therefore, dissociation during dilution**

Of all biopolymers, only nucleic acids fulfil these basic criteria
Strong base pairing – promotes association in presence of NaCl
Strong charge repulsion – promotes dissociation in absence
→ dissociation on dilution
→ association on drying

Life's emergence (as we know it) may require a large close satellite

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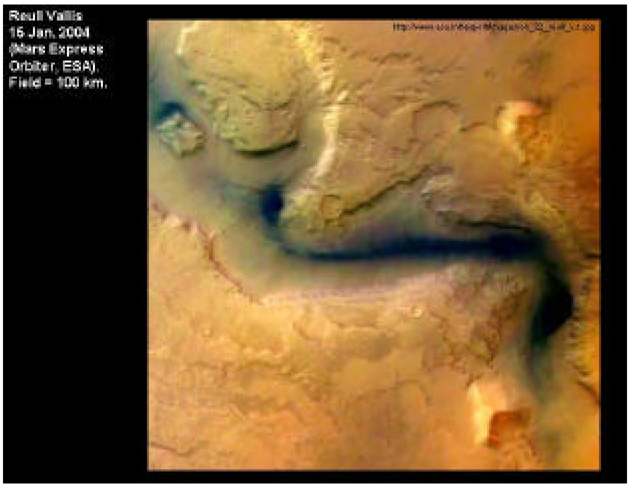
Slide 26. Is there water on Mars?



Slide 27. Earth, Moon, Mars, Phobos; sizes to scale

Slide 28. Endpiece

Picture: New Scientist

References

Lathe, R. (2004). Fast tidal cycling and the origin of life. *Icarus, 168*, 18-22.

Lathe, R. (2005). Tidal chain reaction and the origin of replicating biopolymers. *Int.J.Astrobiol. in press.*

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