## EARLY LIFE IN ROCK PORES DRIVEN BY THERMAL FORCES?

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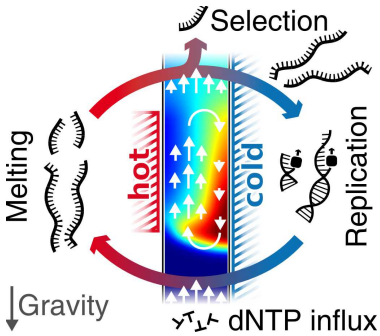
**Introduction:** The Origin of Life is one of the fundamental, unsolved riddles of modern science. Life as we know it is a stunningly complex non-equilibrium process, keeping its entropy low against the second law of thermodynamics. Therefore it is straightforward to argue that first living systems had to start in a natural non-equilibrium settings. Recent experiments with non-equilibrium microsystems suggest that geological conditions should be able to drive molecular evolution, i.e. the combined replication and selection of genetic molecules towards ever increasing complexity.

**Non-Equilibrium Settings:** As a start, we explored the non-equilibrium setting of natural thermal gradients. Temperature differences across rock fissures accumulate small monomers more than millionfold [1] by thermophoresis and convection [2]. Longer molecules are exponentially better accumulated, hyperexponentially shifting the polymerization equilibrium towards long RNA strands [3]. The same setting implements convective temperature oscillations which overcome template poisoning and yield length-insensitive, exponential replication kinetics [4]. Accumulation and thermally driven replication was demonstrated in the same chamber, driven by the same temperature gradient [5]. Protein-free, non-ligating replication schemes can be driven by thermal convection. For example, the hairpins of tRNA can be used for reversible codon-sequence replication, bridging from replication of genes to the translation of proteins [6]. Non-templated polymerization and hybridization- dependent degradation leads to replication-like information transmission [7]. Replication and trapping of DNA persist over long time in a constant influx of monomers, closely approaching the criteria for an autonomous Darwin process.

**Biotechnology Spinoff:** Experiments using non-equilibrium conditions at the microscale are non-trivial. For example, molecules have to be detected selectively with the most sensitive biochemical, optical and microfluidic approaches. Advances of biotechnology in this regime is very fruitful. Our award winning NanoTemper spinoff company, with now more than 70 employees, demonstrated that basic research for the origin of life can lead to cutting edge biotechnology [8][9].

**Environments:** Besides temperature gradients, many more non-equilibrium settings can be imagined and become increasingly accessible to experimentation. For example, geological pH gradients, geological redox potentials or the optical excitation of geological nanoparticles should drive metabolic reactions in a very peculiar way. To be successful, an effort on the origin of life has to be embedded in a strong and very active interdisciplinary background of biology, biochemistry, chemistry, astrogeology and not the least, theoretical modeling at various levels of abstraction.




**Selection for increasing complexity:** The replication of long nucleic acid sequences was required for the evolution of biological complexity during the origin of life; however, short sequences are normally better replicators than long ones. Recently, we showed how a common physical environment provides a simple mechanism to reverse this trend and enables long sequences to flourish [10]. On a similar note, the trap is creating gels from oligonucleotides - and sorts them in a phase transition with equal sequence and single base pair discrimination [11].

**References:** [1] Baaske, Weinert, Duhr, Lemke, Russell & Braun, *PNAS* 104, 9346–9351 (2007). [2] Duhr & Braun, *PNAS* 103, 19678–19682 (2006). [3] Mast, Schink, Gerland & Braun, *PNAS* 110, 8030-8035 (2013). [4] Braun, Goddard & Libchaber, *PRL* 91, 158103 (2003). [5] Mast & Braun, *PRL* 104, 188102 (2010). [6] Krammer, Möller & Braun, *PRL* 108, 238104 (2012). [7] Obermayer, Krammer, Braun & Gerland, *PRL* 107, 018101 (2011). [8] Wienken, Baaske, Rothbauer, Braun & Duhr, *Nature Communications*, 1, 100 (2010). [9] Schoen, Krammer & Braun, *PNAS*, 106, 21649–21654 (2009). [10] Kreysing, Keil, Lanzmich & Braun, Nature Chemistry 7, 203–208 (2015). [11] Matthias Morasch, Dieter Braun, and Christof B. Mast, Angewandte, (2016) doi: 10.1002/anie.201603779.