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Thermal Convection in Hydrothermal Vent Systems: Environments for Integrated Prebiotic Chemistry and Origin of Life Processes

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Hydrothermal vent systems uniquely contain chemically rich microenvironments that embed superimposed thermal gradients and flow phenomena, creating a unique setting for geochemical processes shaping the early stages of life's emergence. But the combination of physico-chemical conditions that optimally promote the assembly of life's building blocks and the role enzymatic reactions play in these settings are not yet fully understood. Here, we report the results of recent studies that address these questions by investigating chemical enrichment dynamics in hydrothermal pore mimicking systems and exploring the integration of enzymatically catalyzed reactions within these frameworks. First, we demonstrate how localized trapping and chaotic mixing within select pore geometries under variable thermal gradients drive the formation of micron-sized phosphatidylcholine vesicles, crucial protocell membrane constituents. Next, we extend our studies to consider enzymatically catalyzed reactions within these microenvironments in the context of DNA replication biochemistry. Our findings reveal how physical and biochemical conditions combine to enable DNA replication under hydrothermally relevant temperature gradients and how these pathways favor the replication of amplicons within a specific range of GC content. This integrative approach demonstrates how physical and chemical mechanisms synergistically orchestrate prebiotic chemical processes. Our studies also establish a foundation to elucidate the complex interdependencies between origin-of-life biochemical processes and the exobiological environments most likely to support them.