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Thermodynamic constraints on the chemical interaction of microbes and minerals in hydrothermal systems

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Significant concentrations of enzymes, nucleotides, nucleic acids, and other biomolecules are present in the fluids of hydrothermal systems which sustain life. Reactions among these molecules and authigenic minerals are an integral part of the life-support systems for the colonies of thermophiles that inhabit these environments. The most familiar examples of this interdependence are the sulfide mineral substrates that support hyperthermophilic life in hydrothermal vent systems. Thermodynamic calculation of the relative stabilities of folded and unfolded proteins as a function of temperature and solution pH indicate that many folded proteins in mammals have high thermal stabilities, especially at extremes of pH. Because this thermal tolerance is genetically engineered, it may well be an inherited evolutionary vestige of the origin of life on Earth in hydrothermal systems. Thermodynamic calculations also indicate that reversible and irreversible reactions among proteins, nucleotides, and other biomolecules generated by hyperthermophilic microbes are functions of pH and the fugacities of O₂, H₂, H₂S, CO₂, and NH₃, which in turn depend directly or indirectly on the mineralogy of the system and the composition and speciation of the aqueous phase. Consequently, the relative stabilities of biomolecules that are requisite for life and the authigenic mineralogy and fluid chemistry of the hydrothermal system are intrinsically

interdependent. Evaluating the chemical potentials responsible for this interdependence makes it possible to assess the extent to which they influence microbial metabolism, which involves both reversible and irreversible reactions and intra- and extracellular mass transfer. Preliminary computer experiments (LaRowe and Helgeson, this volume) confirm that diffusive intracellular mass transfer in microbial cells is coupled to the extracellular environment by an open system network of stationary states in which reversible and irreversible reactions take place simultaneously in subcellular units separated by relatively thin species-specific semipermeable membranes. The overall process is irreversible and demand driven. Hence, it causes ingestion of reactants, selective recycling of products, and export of species such as ATP, e⁻, and H⁺ to other parts of the cell, which provides energy for molecular synthesis and cellular reproduction. The computer experiments and thermodynamic and mass transfer calculations carried out so far (and those to come) have profound implications, not only for understanding the chemical interaction of life with its environment at high temperatures, but also with respect to drug design, disease control, and human health, all of which can benefit substantially from a global thermodynamic approach to understanding cellular metabolism.