

Differential adsorption of nucleic acid bases: Relevance to the origin of life

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The adsorption of organic molecules onto the surfaces of inorganic solids has long been considered a process relevant to the origin of life. We have determined the equilibrium adsorption isotherms for the nucleic acid purine and pyrimidine bases dissolved in water on the surface of crystalline graphite. The markedly different adsorption behavior of the bases describes an elutropic series: guanine > adenine > hypoxanthine > thymine > cytosine > uracil. We propose that such differential properties were relevant to the prebiotic chemistry of the bases and may have influenced the composition of the primordial genetic architecture.

The purine and pyrimidine coding elements of nucleic acids are products of putative prebiotic chemistries that invoke cyanide (1, 2) and have been synthesized in reactions that also yield amino acids (3). The prebiotic availability of these compounds supports the RNA World Hypothesis (4) for the origin of life, which presupposes that the first living system was a polymer(s) of catalytic RNA capable of self-replication that subsequently evolved the ability to encode more versatile peptide catalysts. RNA can act as both information carrier and catalyst (5) and, in the laboratory, can be coerced into different catalytic functions through directed Darwinian evolution (6).

Despite these properties, there are severe difficulties with the *de novo* appearance of RNA, and, even in the most optimistic scenario, information-bearing molecule(s) capable of self-replication must have first formed fortuitously from an astronomical range of possibilities (7). Although RNA-mediated catalysis and the nonenzymic polymerization of nucleotides (8, 9) are well demonstrated, nucleic acid structure incorporates carbohydrate moieties. Formaldehyde, a seemingly ubiquitous compound, is regarded as the most plausible precursor of carbohydrates; however, cyanohydrin (glyconitrile) is the major highly stable product of reactions between formaldehyde and cyanide, withdrawing the latter from being a putative source of bases and amino acids (10). The recovery of nonbiogenic amino acids and bases from extraterrestrial debris (11) suggests the spatial-temporal separation of formaldehyde and cyanide. Life may have been initiated in the absence of carbohydrates, and it has been proposed that modern biology was preceded by a non-nucleic acid informational architecture (12, 13).

Aperiodicity is required to convey information (14), and it has been demonstrated that aperiodic structures can self-assemble from aqueous mixtures of purine and pyrimidine bases adsorbed onto the surface of an uncharged inorganic crystalline mineral (15). The spontaneous formation of such structures suggests the existence of an organic, nonpolymeric informational architecture that may have had relevance to the origin of life.

The adsorption of organic molecules onto inorganic solids has long been considered a relevant prebiotic process (16). The purine and pyrimidine bases adsorb spontaneously from aqueous media onto inorganic solids and have been observed on the surfaces of graphite (17–21), MoS₂ (15, 18–21), crystalline gold (22), and clays (23, 24). Scanning probe microscopy (SPM) studies have shown that the bases are planar-arranged on these surfaces like jigsaw puzzle pieces. They are stabilized by van der Waals interactions with the underlying surface and by hydrogen

bonds between adjacent molecules (15, 18–21, 25), a configuration originally postulated on the basis of thermodynamic measurements made at the mercury–water interface (26). The hydrogen bonds between the bases are drawn from a discrete set of possible interactions including those of Watson–Crick pairing found in nucleic acids (15). The monolayers can be likened to nucleic acid molecules because the sugar-phosphate scaffold also supports an arrangement of bases. Each position in the scaffold can be mapped to the next by a simple translation operation and so resembles an underlying crystal.

Materials and Methods

We determined the adsorption isotherms by frontal analysis (27). Natural graphite crystals (Superior Graphite, Chicago, IL; batch no. 9850) were fractionated according to size by sieving. Particles in the range 90 to 250 μm were loosely packed (1.42 g) into a 150 mm \times 3.9 mm (inner diameter) stainless steel HPLC column. The Braunauer, Emmett, and Teller surface area for the graphite fraction was determined to be 0.7 m²·g⁻¹. The column was connected to a computer-controlled HPLC solvent delivery system (Waters). Detection of the eluted bases was achieved by using a UV flow detector set at 260 nm. The temperature of the column was maintained by a column heater, and the solvents were degassed by in-line helium sparging. Base solutions were prepared by dissolving the pure solids (Sigma) in milliQ (Millipore) water and then accurately determining the concentration of the filtered solutions by UV spectrophotometry (28). Stepwise increases in the concentrations of the water-base mixtures were achieved by programming the solvent delivery system to deliver abrupt step gradients to the column. The retention times of the breakthrough fronts were determined by numerical integration to obtain the midpoints of the breakthrough curves by using the program ADSORPSTATION (29). The isotherm loading diagrams were generated by the transformation of the internal retention times by using the mass balance equation implemented in ADSORPSTATION. Each of the isotherms (Fig. 1) is the average of triplicate experiments and have standard deviations in the range of 0.5% to 2% for adenine (A), hypoxanthine (H) and thymine (T), and 5% to 10% for guanine (G), cytosine (C), and uracil (U).

Results and Discussion

At the solid–liquid interface, the adsorption isotherm is the thermodynamic property describing the distribution of molecular solute species between the fluid solvent phase and the solid sorbant phase. We have determined the single solute adsorption isotherms for the biological purine and pyrimidine bases at the graphite–water interface at 30°C (Fig. 1). Comparison of the isotherms shows markedly different behavior of the bases and describes an elutropic series; G > A > H > T > C > U. In a multisolute system, compounds to the left of such a series displace those to their right because they out-compete them for

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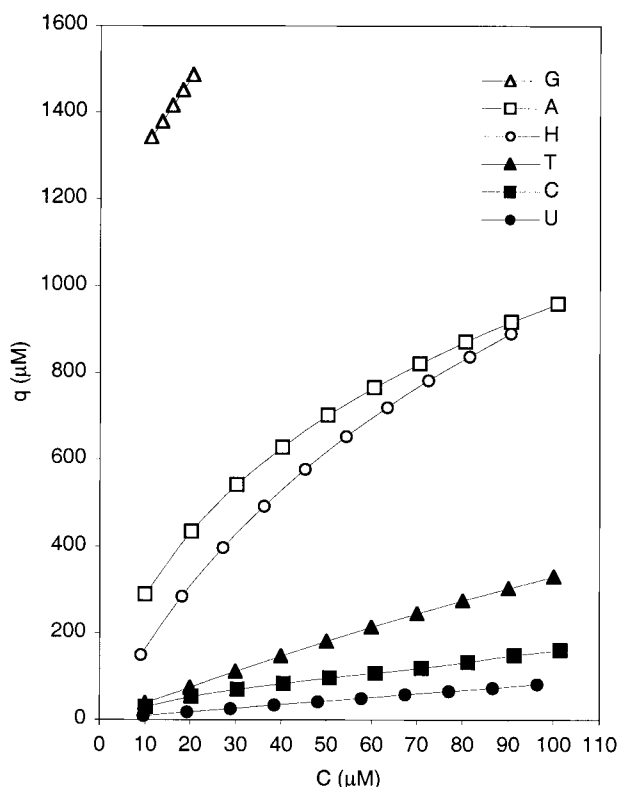


Fig. 1. The single solute adsorption isotherms for the purine and pyrimidine bases at the graphite–water interface at 30°C. The concentrations of the bases in the solid phase (q) are at equilibrium with bases in the liquid phase (C).

surface adsorption sites. However, conditions exist where mixtures of different bases can coexist on a surface, presumably because of their ability to interact with each other by hydrogen bonding (15, 23). The physical origin of this disparate behavior is contributed to by molecular differences in the van der Waals surface area of the bases (15) and variability in their solubility in water ($\text{g}/100 \text{ ml}^{\text{Temp}}$: G, $0.004^{40^\circ\text{C}}$; A, $0.09^{25^\circ\text{C}}$; H, $0.07^{19^\circ\text{C}}$; T, $0.4^{25^\circ\text{C}}$; C, $0.77^{25^\circ\text{C}}$; and U, $0.36^{25^\circ\text{C}}$; ref. 28). Electrochemical measurements made at the mercury–water interface show that maximal adsorption of the bases occurs at the potential of zero charge (30). The proposed mechanism of monolayer formation relies on the spatial restriction of solvent at the uncharged interface. Here, hydrogen bonding interactions between the bases are favored. In solution, the molecules are surrounded by water molecules and remain dissolved (31). Although graphite is not considered a dominant prebiotic material, uncharged mineral surfaces were present in prebiotic times and would have

facilitated the accretion of organic matter. Relevant examples come from the mineral families: zeolites, feldspars, and silicas (32, 33), and there is also recent evidence that adenine and purine can adsorb to uncharged sites on the surface of pyrite (J. Bebie and M. A. A. Schoonen, www.rsc.org/is/journals/current/geochem).

The low yields of the bases in abiotic chemical reactions and their susceptibility to hydrolysis in the aqueous phase have been used to argue against their utilization at the origin of life (35) and stability in hydrothermal systems (36). However, these arguments have not considered the effects of inorganic solids, which significantly alter the physical state of the system. The isotherms show that the phase equilibria for the purines are far displaced toward adsorption, which has both thermodynamic and kinetic consequences. Adsorption facilitates the removal of the bases from the chemical equilibrium expression, and the resulting non-equilibrium thermodynamics provides a continuous and negative Gibbs-free energy to drive the synthesis of the bases. Solidification favors protection of the bases from hydrolytic decomposition because the adsorbed structures exclude water (15, 18–20) and so provide a kinetic barrier to hydrolysis. Both effects would contribute to the prebiotic accumulation of these molecules.

Scanning probe microscopy analysis of monolayers formed by the evaporation of purine and pyrimidine mixtures of A + U on MoS_2 confirmed the presence of aperiodic structure, but only in the presence of a large excess of the lower adsorbing U. More equivalent ratios resulted in surface structure dominated by A crystallinity, but such periodic structures have little capacity to convey information (15). The perceived problems with pyrimidine availability and stability have led to the suggestion of purine-only genetic systems (34, 37). The weaker adsorption of C, T, and U augments the case against their utilization in the primordial genetic architecture. It may be fortuitous that the yield of the stronger displacing G in abiotic reactions is about 10 times lower than that of A (3) and suggests a scenario of mixed purine-only aperiodic monolayer systems.

Could other organic compounds have acted to displace the bases? Analysis of the most plausible prebiotic chemistries indicates a range of products that are likely to have existed (1, 2). Of the heterocycles, only a few are capable of in-plane hydrogen bonding. The bases appear uniquely suited to dominate the solid–liquid interface through the spontaneous self-assembly of hydrogen-bonded supramolecular architectures. The putative informational capabilities of these structures provides compelling arguments for further investigation.

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