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Abiotic Carbon Cycles Driven by Natural Radioactivity: Mechanistic Insights, Conceptual Frameworks, and Geological Contexts

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Low-temperature radiolytic organic synthesis is a plausible abiotic organic-generating pathway[1–3]. This radiolytic pathway is critical for constraining the abiotic baseline of organic compounds, evaluating chemosynthetic habitability on early Earth and analogous planetary environments, and thereby informing life detection strategies[4]. It also expands the search for habitability beyond focusing just on photosynthesis. However, the full spectrum of radiolytic mechanisms, the geochemical controls governing their prevalence and magnitude, and their integration into the broader carbon cycle remain unclear.

This study provides mechanistic insights into radiolytic organic formation by constructing comprehensive radiolysis networks based on existing laboratory evidence from the literature and physical chemistry databases (e.g., NIST). These networks elucidate stepwise radiolytic transformations of simple, ubiquitous carbon sources—dissolved inorganic carbon (DIC), CO_2, carbonate minerals, and CH_4—into diverse C_1-C_3 organic species. Radiolytic inorganic-to-organic conversion typically follows this common pathway: inorganic carbon → radical precursors (e.g., $CO_2^{\bullet-}$) → formic and oxalic acids → other organic species. However, mechanisms driving this pathway depend on water availability and therefore differ fundamentally between DIC and carbonate minerals. In addition, the radiolysis networks outline a conceptual abiotic carbon cycle driven by natural radioactivity, connecting inorganic carbon and CH_4 to a diversity of organic compounds.

Integrating the large-scale abundance and distribution of radionuclides in common rocks, the hydrogeosphere, and carbon sources reveals geochemical controls on this radiolytic carbon cycle. While Earth's subsurface hosts all required components, the prevalence and magnitude of the radiolytic carbon cycle are likely highly localized, depending on the extent of water-rock interactions that assemble these components and the rates of individual pathways and/or steps.

Overall, the mechanistic insights from this study provide a foundation for understanding and simulating how natural radioactivity can drive the chemical evolution of inorganic or simple C1 carbon source (e.g., CH_4) into diverse organic compounds on Earth or other planetary bodies and their implications for chemosynthetic habitability and life detection.

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