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# Modeling Sr isotope fractionation to trace fluid evolution in Archean hydrothermal systems: insights from orogenic gold deposits in Québec, Canada

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Rayleigh fractionation modeling was applied to stable strontium isotope ($\delta^{88/86}$Sr) data from Archean hydrothermal carbonates in order to evaluate progressive fluid evolution during carbonate precipitation. Using previously reconstructed fluid compositions and calculated carbonate–fluid fractionation factors ($a_{carbonate\text{-}fluid}$), we investigated the observed isotopic variability under mesothermal conditions (250–500 °C) in two Archean hydrothermal systems associated with orogenic gold mineralization in Québec, Canada: the Augmitto-Bouzan deposit and the Val-d'Or orogenic gold vein field. For the Augmitto-Bouzan deposit, $\delta^{88/86}$Sr carbonate values range from -0.28‰ to 0.48‰, and modeled $\delta^{88/86}$Sr fluid values range from −0.24‰ to 0.53‰, with nearly constant $a_{carbonate\text{-}fluid}$ (≈ 0.99995) and very low DSr values (≈ $10^{-4}$–$10^{-3}$). Rayleigh simulations─of Sr removed from fluid ($f_{Sr}$ = 0–0.9) indicate minimal isotopic evolution of the residual fluid. The required initial $\delta^{88/86}$Sr values remain close to the modeled final compositions, even at high degrees of precipitation. These results suggest near-equilibrium conditions, limited kinetic effects, and a system largely buffered by fluid composition rather than progressive isotopic evolution. In contrast, the Val-d'Or dataset exhibits significantly higher and more variable DSr values (up to ≈ 0.33) and fractionation factors ($a_{carbonate\text{-}fluid}$ down to ≈ 0.99955). Rayleigh modeling demonstrates that small variations in $a_{carbonate\text{-}fluid}$ produce substantial shifts in the required initial $\delta^{88/86}$Sr fluid values. High $\delta^{88/86}$Sr carbonate values observed in Val-d'Or orogenic gold vein field (ranging from 0.39‰ up to 1.05‰) can be reproduced without multiple isotopically distinct fluid sources if carbonate precipitation occurred under kinetically controlled, non-equilibrium conditions. Modeled scenarios using plausible initial fluid compositions (e.g., $\delta^{88/86}Sr_{initial}$ ≈ 0.55–0.82‰) indicate a highly dynamic system in which progressive carbonate precipitation and variable fractionation exert major control on fluid isotopic evolution. Comparison of both systems reveals contrasting fractionation regimes: the Augmitto-Bouzan deposit records near-equilibrium behavior with limited Rayleigh effects, whereas Val-d'Or reflects strong kinetic conditions where $a_{carbonate\text{-}fluid}$ variability dominates isotopic outcomes. These results demonstrate that elevated $\delta^{88/86}$Sr values do not necessarily require multiple fluid sources, but may instead reflect precipitation-driven isotopic fractionation.