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The Nanoscale Choreography of Organic Molecules and Nonclassical Mineral Formation

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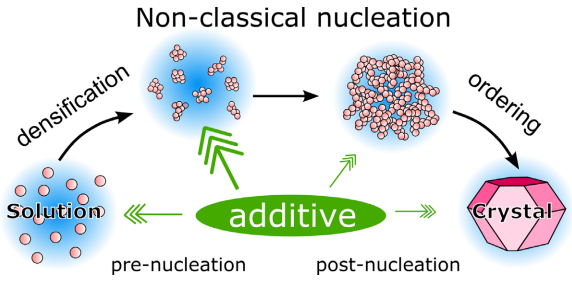

Small quantities of organic additives play a critical role in directing the crystallization of minerals in natural and engineered environments. However, the exact mechanisms governing these complex organic–mineral interactions, particularly during the earliest stages of (bio)mineral formation, remain challenging to resolve, especially because traditional interaction models fail to account for nonclassical nucleation pathways. To illuminate the nanoscale choreography of organic molecules and multistep nucleation processes, we integrated time-resolved in situ X-ray scattering with continuous physicochemical monitoring. This approach allows us to track the structural and chemical evolution of minerals from initial aqueous complexation to their final crystalline phases.

Our observations [1,2] reveal that crystallization proceeds via nonclassical, multistep nucleation pathways involving prenucleation clusters and amorphous intermediates. Within these pathways, diverse minerals exhibit distinctly different phase transitions, ranging from the gradual ordering of disordered intermediates to abrupt structural transformations. In these varying scenarios, the influence of additives extends beyond classical thermodynamic models, such as simple ion-binding or surface attachment [3]. Instead, additives exert their primary control during the prenucleation stage by directly interacting with different precursor phases [4-6]. Notably, these molecules exhibit a complex dual role, capable of simultaneously delaying certain stages of multistep nucleation while accelerating others.

By monitoring the nanoscale evolution of these systems from amorphous precursors to crystalline phases, we highlight the multifaceted impact of organic additives on macroscopic crystallization rates. Unraveling how trace molecules dictate mineral nucleation provides the key tools for predicting mineral formation across diverse geochemical settings, spanning natural (bio)mineralization processes, carbon storage, and the engineering of sustainable building materials.

References

[1] Madeja et al, Cem. Con. Res. 173, 107258 (2023); [2] Kellermeier et al, Angew. Chem. Int. Ed. e202408429 (2024); [3] Nicoleau et al. Cem. Con. Res. 124, 105837 (2019); [4] Ossorio et al. Minerals 7, 140 (2017); [5] Duchstein et al. Angew. Chemie 61, e202208475 (2022); [6] Baken et al. Nat. Commun.17, 1925 (2026).