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Reversible anaerobic methane oxidation drives organic matter preservation and mineral authigenesis in a methane seep off Madagascar

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Cold seeps are dynamic environments where elemental cycling reflects tight coupling between biotic and abiotic processes driven by rising fluids. Isotope dynamics in cold seep sediment have been extensively studied to analyze the sources of methane (CH_4) and seepage-driven carbon cycling in marine sediment. Yet, the mechanistic links between microbial reactions, authigenic mineral formation, and long-term sedimentary signal preservation remain poorly constrained.

We analyzed long sediment cores from a cold seep and reference site near NW Madagascar, determining stable C, S, O isotopic composition and bulk chemistry, as well ^{14}C-dating, and using reaction-transport modeling to link the current porewater and solid geochemical state to its millennial evolution and assess the role of microbially-mediated cycling of reduced carbon pools and mineral formation.

Organic carbon (OC) was isotopically depleted throughout the core compared to the reference site, despite the low growth yield associated with anaerobic methane oxidation (AOM) and the supposed labile nature of fresh assimilated materials. Modeling indicates a preservation mechanism is required, and further chemical analysis shows that CH_4-derived carbon is stored in carbonates. The inorganic carbon and oxygen in carbonates showed a strong anticorrelation. The temperature difference between tropical surface water and deep porewater appears responsible for the isotope effect, letting the isotopic values form a measure for the degree of mixing between biogenic and authigenic minerals. Furthermore, we examined the isotopic depletion of CH_4 within the AOM zone, which has previously been attributed to either methanogenesis or reversible AOM. However, the low background reactivity of OC and low pyritization rates at our site indicate negligible methanogenesis. Modeling instead reproduces the profile primarily through reversible AOM and the dissolution of methane gas into the dissolved phase.

The reaction-transport model integrates isotope effects of multiple biogeochemical pathways, physical mixing induced by gas ebullition, and the conversion of iron (oxy-)hydroxides into pyrite. Coupling these processes over ~10 m and ~36 kyr yields an excellent fit to the data. It reveals the strong coupling between biotic and abiotic processes and highlights the importance of integrated, quantitative assessment of complementary datasets to delineate the microbial processes responsible for the lasting sedimentary imprint.