

Methane seeps in an anoxic seaway: linking carbonate geochemistry, fluid flow, and faunal structure at a long- lived seep field in the mid-Cretaceous North American Western Interior Seaway during Oceanic Anoxic Event 2

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Methane emissions at hydrocarbon seeps drive diverse biogeochemical interactions that create productive deep-sea chemosynthetic ecosystems. A fundamental process is the microbially-mediated anaerobic oxidation of methane (AOM) via sulfate reduction, which generates sulfide that fuels free-living and chemosymbiotic thiotrophs. Chemosymbiotic macroinvertebrates actively shape seep habitats by enhancing AOM rates, detoxifying sediment, and oxygenating porewaters, facilitating colonization by less-specialized metazoans sensitive to high sulfide, low oxygen conditions. AOM also produces ¹³C-depleted bicarbonate, promoting extensive seep-associated carbonate (SAC) formation with characteristically light $\delta^{13}\text{C}$ signatures, reflecting the imprint of AOM-derived carbon on the DIC pool. Fossil SACs therefore serve as biogeochemical archives for reconstructing ancient seep dynamics.

We studied a 14-m section of the Cenomanian-Turonian-aged Tropic Shale (Utah, USA) that preserves a near-continuous record of seepage in the Cretaceous Western Interior Seaway (WIS) during Oceanic Anoxic Event 2 (OAE2; ~94 Ma), a major carbon cycle perturbation likely driven by submarine LIP-volcanism. We reconstructed SAC formation environments and analyzed shifts in macroinvertebrate communities in response to changing seep dynamics and broader OAE2 perturbations. The morphology, petrography, $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ signatures, and paleoecology of SACs were characterized to interpret variations in seepage intensity and carbonate formation. We find a reduction in the size, distribution, and fauna of SACs up-section: meter-scale-sized, fossiliferous carbonates transition to small, cm-scale-sized SACs with depauperate fauna, concurrent with heavier $\delta^{13}\text{C}$ signatures and reduction of chemosymbiotic bivalves. This suggests reduced methane transport, AOM, and carbonate formation. However, fossiliferous SACs associated with effusive methane seepage coincide with intense periods of anoxia and euxinia, which largely eliminated benthic faunal diversity in surrounding WIS environments. We therefore interpret seep community changes as primarily driven by local (seep) environmental factors rather than broader regional perturbations. This highlights the critical role of specialized chemosymbiotic taxa in the overall functioning of extreme

environments such as seeps, as their presence– or absence– exerts strong controls on seep dynamics, as well as the influences of chemosynthetic environment on broader marine biodiversity. Given the widespread spatiotemporal distribution of seeps, continued research into their geobiology may provide valuable analogs for biogeochemical processes on planetary bodies where methane cycling and carbonate precipitation could occur.