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Brachiopod geochemical records from across the Carboniferous seas of North America: Evidence for salinity gradients, stratification, and circulation patterns

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ABSTRACT

Stable isotopic analyses of >100 well-preserved Carboniferous brachiopod shells, representing two time slices from across North America, reveal systematic regional changes in environmental conditions. For both of the time slices studied, the Chesterian (latest Mississippian) and the Virgilian (latest Pennsylvanian), $\delta^{18}O$ and $\delta^{13}C$ show a stepwise decrease moving across the continent from modern-day west to east. Higher $\delta^{18}O$ in the west reflects greater water depths, less freshwater input, and more direct upwelling influence from cool, open-marine waters than in the east. Modelling based on these regional isotopic data indicates salinity reductions on the order of ~1–4 psu in the Appalachian Basin relative to the Midcontinent Basin for the Virgilian time interval over a range of reasonable thermal gradient and $\delta^{18}O_{fw}$ assumptions. The magnitude of this gradient is similar to those of modern-day Hudson Bay and the Panama Bight, which exhibit permanent haloclines driven by freshwater discharge. Considering existing paleoecological evidence for freshening, the lack of more dramatic benthic freshening suggests that the depth of a regional halocline was shallower than the depths inhabited by thick-shelled stenotopic brachiopods, although other lines of evidence are necessary to verify the strength of the halocline. Estimated $\delta^{18}O$ temperatures for Appalachian Basin brachiopods are ~3–5 °C cooler than those of coeval conodonts, due to either slightly warmer, fresher surface waters or uncertainty in the phosphate ^{18}O paleothermometer. Despite discrepancies in calculated temperatures, the magnitude of the regional isotopic gradient derived from brachiopod and conodont proxies is similar after making appropriate glacioisotopic and water depth corrections. A decreasing $\delta^{13}C$ trend toward the east (southern paleolatitude) likely reflects greater restriction and terrestrial influence near the sea's tropical shoreline. Trace element trends are less consistent and are affected by species and metabolism. Erratic variations in Mg/Ca concentrations, even among pristine samples of the same genera with similar $\delta^{18}O$ values, and unrealistic Mg/Ca-derived temperatures justify continued caution in applying existing Mg/Ca thermometer equations to Paleozoic brachiopods.

1. Introduction

Regional salinity gradients in restricted marine settings exert a dominant influence on a variety of geologically important processes. These contrasts in salinity, both vertical and lateral, work alongside other key boundary conditions to control ecology and biological diversity, sedimentation, and organic matter production and preservation in modern-day estuaries and continental seas (e.g. Tyson and Pearson, 1991; Robertson et al., 1993; Eyre and Balls, 1999; Hopkinson et al., 1999; Zettler et al., 2007; Algeo et al., 2008). A similar gradient may have helped control benthic redox conditions in the North American continental sea during the Pennsylvanian, permitting deposition of extensive black, dysoxic shale facies despite relatively shallow water conditions (Algeo et al., 2008; Algeo and Heckel, 2008). So-called "estuarine-type" circulation models have long figured into geological characterizations of the sea (cf. Heckel, 1977, 1991; Hatch and Leventhal, 1992; Olszewski and Patzkowsky, 2008) but are not universally accepted (e.g. Tyson and Pearson, 1991). Furthermore, interpretations of recently-collected conodont $\delta^{18}O$ data have challenged whether significant regional salinity differences across the sea persisted into the Late

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Pennsylvanian (Joachimski and Lambert, 2015). Here, we present a compilation of new and previously published geochemical analyses of Virgilian (latest Pennsylvanian) brachiopod shells from across the North American continent, as well as data from the Chesterian (latest Mississippian) for comparison, to document regional changes and evaluate evidence for geochemical partitioning across the sea at benthic depths.

Naming conventions for the North American sea have varied in published literature. To avoid confusion, we will refer to the North American continental sea during the Virgilian time slice as the Late Pennsylvanian Midcontinent Sea (LPMS) after Algeo and Heckel (2008). When referring to the Chesterian time interval, or speaking more generally about the Carboniferous Period as a whole, we use the terms "Carboniferous sea" or "continental sea."

2. Geological background

At its climax in the late Pennsylvanian, the North American Carboniferous sea stretched from the tropics, bounded to the south by the equator-parallel Alleghenian uplift belt, north and west into subtropical latitudes (15°–20° N) to the edge of the craton, where the sea interfaced with the open Panthalassic Ocean (Fig. 1; Heckel, 1977; Algeo et al., 2008). Along its equatorial margin, the continental sea would have received a massive influx of freshwater, mostly as extensive runoff from the tropical mountain belt. This influx would have tapered to the north in the subtropical portion of the sea, which would have also been more proximal to ocean upwelling (Algeo and Heckel, 2008; Algeo et al., 2008).

Heckel (1977) crystallized the latitudinal interplay between warmer continental and cooler oceanic water masses into the conceptual "quasi-estuarine circulation" model for benthic dysoxia in the LPMS. Presumably, warmer, possibly less saline surface waters formed a lens over cooler marine waters advected from the open ocean. Resulting density stratification prevented the water column from overturning, thereby perpetuating low-oxygen conditions during highstands and leading to the deposition of black shales (Heckel, 1977). Algeo et al. (2008) and Algeo and Heckel (2008) reformulated this hypothesis as the "superestuarine circulation" model (Fig. 2), which more strongly emphasizes the role of salinity-driven stratification. The "superestuarine" model proposes that tropical freshwater influx from the continental

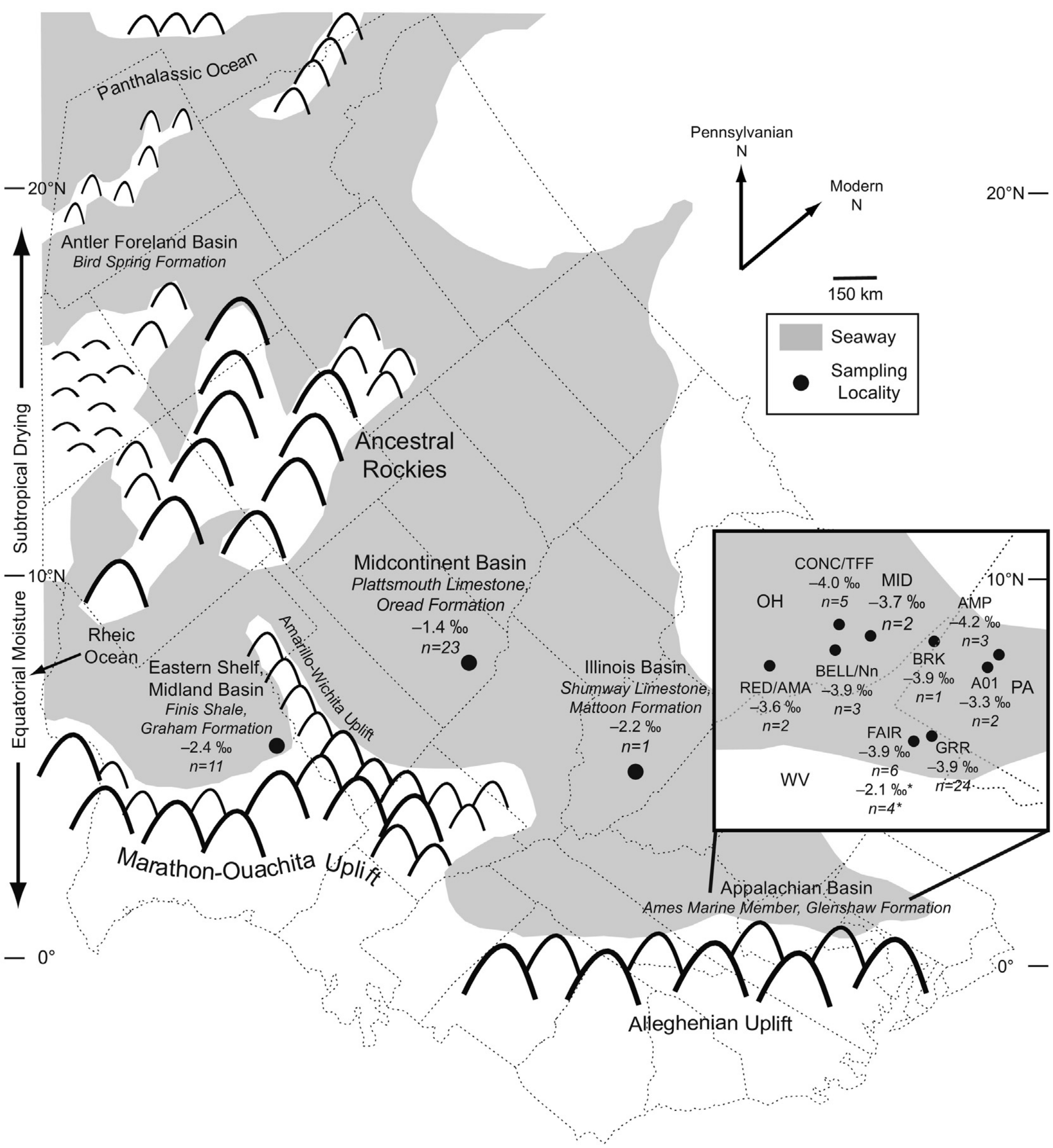

Fig. 1. Paleogeography of the North American continental sea during the late Pennsylvanian, showing sampling locations and average brachiopod $\delta^{18}O$ values for the Virgilian time slice. Inset shows locations and names of the Appalachian Basin sampling sites. Asterisk indicates anomalous samples at FAIR locality collected by R. Flake. OH = Ohio; WV = West Virginia; PA = Pennsylvania. Paleogeography modified from Algeo and Heckel (2008) and Blakey (2011).

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