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# Tropical weathering of the Taconic orogeny as a driver for Ordovician cooling

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It is widely accepted that long-term climate variability is controlled primarily by $CO_2$ with other greenhouse gases and planetary albedo playing an important, but subsidiary, role. On million-year timescales, $CO_2$ is sourced predominantly from volcanic outgassing, consumed predominantly by silicate weathering, and modulated by the silicate weathering feedback (e.g., Berner, 2006). As summarized by Saltzman (2017), the relative importance of $CO_2$ sources and sinks as the driver of transitions between non-glacial and glacial climate regimes is a matter of debate and proxies for both come with caveats. As silicate weathering is dependent on latitude, topography, temperature, and precipitation, improved geological and paleogeographic constraints offer the potential to better predict how silicate weathering has changed through time. In Swanson-Hysell and Macdonald (2017), we examined these constraints and argued that increased planetary weatherability led to lower steady-state $CO_2$ through the exhumation of arc-related lithologies during the Taconic orogeny. We emphasized the importance of exhumation occurring in an east-west orientation within the equatorial humid belt, rather than the arid subtropics, as well as the high weatherability of exhumed arc-ophiolite rocks. Both factors enhance the plausibility of the Kump et al. (1999) hypothesis that the Taconic orogeny significantly modulated Ordovician climate. We also argued that compiled proxies for local weathering provenance ($\varepsilon_{Nd}$) are consistent with this volcanic-weathering hypothesis, as are global records that are influenced by weathering inputs (e.g., $^{87}Sr/^{86}Sr$; Berner, 2006). We acknowledged that the Taconic orogeny was not the sole change in tectonic boundary conditions at the time, and other arc systems, such as those in the Central Asian Orogenic Belt (CAOB), likely enhanced global weatherability. However, most of the ophiolite-bearing sutures in the CAOB are Late Paleozoic in age, not Cambrian (Furnes et al., 2014). Ordovician large slab ophiolites in the Caledonian-Appalachian belt, which extend through Norway to the M'Clintock orogen on Ellesmere Island, are among the largest and best preserved in the geological record despite erosion and structural reworking in subsequent orogenesis (Furnes et al., 2014).

Landing (2018) argues that fluctuations in Ordovician climate were largely not controlled by $CO_2$, but instead by non-glacial eustatic sea level. His hypothesis is that the Ordovician was characterized by periods of "hyperwarming" when high eustatic sea level lowered planetary albedo and increased water vapor in the atmosphere. He envisions that these non-glacial global eustatic sea-level changes were large, rapid, and repeated (Landing, 2012, his figure 2) and that non-glacial global eustatic sea-level fall (with an unclear mechanism) initiated cooling that led to the Hirnantian glaciation (Landing, 2018). This hypothesis has a number of weaknesses, with the most glaring being that it invokes large and rapid changes in ice-free global eustasy. Changes to sea level in the absence of waxing and waning ice sheets should be both gradual and small. Rowley (2017) estimates such non-glacial eustatic sea-level change to be $25 \pm 22$ m over the past 170 m.y. In contrast, regional tectonics can cause subsidence and uplift on scales of several kilometers over millions of years. As discussed by Macdonald et al. (2017), major Ordovician sequence boundaries in New England were driven by Taconic tectonism, and the Sauk-Tippecanoe sequence boundary itself may be associated with plate reorganization and subduction beneath Laurentia, similar to the modeled effects of dynamic subsidence in the Cretaceous interior seaway (Mitrovica et al., 1989). Inferring large-scale rapidly fluctuating global eustatic sea-level variation from facies in the Taconic allocthon, as done by Landing (2012), is problematic.

Landing (2018) argues that the postulated high eustatic sea level would have eliminated the precipitation gradient between the tropics and subtropics and that a location of the Taconic orogenic belt within 10º of the equator, as opposed to 20º, would have no effect on its weatherability. This argument neglects the fact that the intertropical convergence zone arises from large-scale atmospheric circulation. Although the edge of the tropical belt has certainly migrated in different climates and paleogeographies, model runs at a quadrupling of present-day $CO_2$ show such shifts to be relatively small (0–3º; Davis et al., 2016).

We agree with Saltzman's (2017) assessment that "the existing Ordovician $\delta^{18}O$ paleotemperature curve is relatively poorly constrained in the interval of changing $\varepsilon_{Nd}$ and $^{87}Sr/^{86}Sr$." The interpretation put forward by Landing (2018) that the $\delta^{18}O_{apatite}$ data of Trotter et al. (2008) show a rise at ca. 460 Ma is neither robust within the uncertainty of the relevant data nor reflective of the inherent variability between samples seen in higher-resolution Silurian data (Trotter et al., 2016; Swanson-Hysell and Macdonald, 2017, our figure 2). Even the more standard interpretation of Ordovician cooling to stasis to cooling based on the Trotter et al. (2008) data is arguably an over-interpretation given these caveats. Improving this proxy record through the Middle to Late Ordovician is a pressing need to advance understanding of this critical interval of Earth history.

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