THE GEOLOGICAL SOCIETY OF AMERICA®

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

Nicholas L. Swanson-Hysell[1] and Francis A. Macdonald[2]
[1]Department of Earth and Planetary Science, University of California, Berkeley, California 94720-4767, USA
[2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

ABSTRACT

The Earth's climate cooled through the Ordovician Period leading up to the Hirnantian glaciation. Increased weatherability of silicate rocks associated with topography generated on the Appalachian margin during the Taconic orogeny has been proposed as a mechanism for Ordovician cooling. However, paleogeographic reconstructions typically place the Appalachian margin within the arid subtropics, outside of the warm and wet tropics where chemical weathering rates are highest. In this study, we reanalyze the paleomagnetic database and conclude that Ordovician constraints from cratonic Laurentia are not robust. Instead, we use paleomagnetic data from well-dated volcanic rocks in the accreting terranes to constrain Laurentia's position given that the Appalachian margin was at, or equatorward of, the paleolatitude of these terranes. To satisfy these allochthonous data, Laurentia must have moved toward the equator during the Ordovician such that the Appalachian margin was within 10° of the equator by 465 Ma. This movement into the tropics coincided with the collision and exhumation of the Taconic arc system, recorded by a shift in neodymium isotope data from shale on the Appalachian margin to more juvenile values. This inflection in detrital neodymium isotope values precedes a major downturn in global seawater strontium isotopic values by more than one million years, as would be predicted from a change in weathering input and the relatively long residence time of strontium in the ocean. These data are consistent with an increase in global weatherability associated with the tropical weathering of mafic and ultramafic lithologies exhumed during the Taconic arc-continent collision. A Taconic related increase in weatherability is a viable mechanism for lowering atmospheric CO_2 levels through silicate weathering contributing to long-term Ordovician cooling.

INTRODUCTION

Ordovician strata record the transition from an Early Ordovician ice-free world to end-Ordovician glaciation and mass extinction (Cooper and Sadler, 2012). Several hypotheses have been proposed to account for this cooling and the initiation of glaciation including: increased carbon burial (Brenchley et al., 1994), aerosol release from volcanism (Buggisch et al., 2010), decreased volcanic outgassing (McKenzie et al., 2014), increased silicate weathering due to topography associated with the Taconic orogeny (Kump et al., 1999), and increased weathering of fresh volcanic rocks (Young et al., 2009). Oxygen isotope data from brachiopods and conodonts indicate that Hirnantian glaciation is the culmination of longer term cooling from 480 to 445 Ma (Trotter et al., 2008; Veizer and Prokoph, 2015). Although short-term perturbations such as increased organic carbon burial inferred from positive carbon isotope excursions, changes in ocean circulation, or sulfur aerosol release could account for transient cooling associated with the Hirnantian glacial maximum, tectonic changes associated with long-term changes to CO_2 sources or sinks are required to drive ~35 m.y. of cooling. An increase in global weatherability can lead to CO_2 levels decreasing through increased silicate weathering, associated delivery of alkalinity to the ocean, and sequestration of bicarbonate in chemical sediments. The silicate weathering feedback can lead to stabilization at a lower steady-state CO_2 level (Kump et al., 1999).

Arc-continent collision is a tectonic process that can combine the mechanisms for cooling outlined here and lead to a decrease in volcanic outgassing through the death of an arc, and an increase in silicate weathering through increased topography and the exhumation of highly weatherable mafic and ultramafic rocks (Reusch and Maasch, 1998; Jagoutz et al., 2016). Arc-continent collision associated with the Taconic orogeny has been suggested to be associated with Ordovician cooling (Reusch and Maasch, 1998), but paleogeographic reconstructions typically place the Taconic arc system outside of the tropical weathering belt and within the arid subtropics (e.g., Mac Niocaill et al., 1997; Domeier, 2016; Torsvik and Cocks, 2017). Modern evaporite belts and the paleolatitude of evaporites constrain the arid subtropics to be persistently between latitudes of 15° and 35° (Evans, 2006). Given that weathering rates are strongly dependent on temperature and precipitation, and that weathering rates within basaltic watersheds in the tropics are approximately an order of magnitude higher than those in mid-latitudes (Dessert et al., 2003), such a subtropical position would likely preclude major CO_2 drawdown associated with arc-continent collision (Jagoutz et al., 2016). Consequently, the reconstruction of the paleolatitude of the orogeny is critical to the hypothesis that an increase in silicate weatherability associated with the Taconic orogeny drove a portion of Ordovician cooling. Did the Taconic arc-continent collision occur in the arid subtropics or in the wet tropics?

TECTONICS OF THE TACONIC OROGENY

The Taconic orogeny encompasses Ordovician collisional and accretionary events between volcanic arcs that formed within the Iapetus Ocean and the Appalachian margin of Laurentia. The Taconic orogeny has been separated into three broad phases (van Staal and Barr, 2012): Taconic 1 (495–488 Ma) includes local amphibolite-grade metamorphism in the arc terranes; Taconic 2 (488–461 Ma) spans the collision of the leading edge of the Taconic arc system with distended fragments and promontories of the Laurentian margin and the initiation of north-directed subduction; and Taconic 3 (461–445 Ma) comprises later arc accretion events. By ca. 465 Ma, amalgamated arc terranes and fragments of the margin were thrust onto Laurentia, and delivered arc detritus, including detrital chromite, into marginal basins (e.g., Hiscott, 1978; Macdonald et al., 2017).

The colliding Taconic arc system extended west (paleocoordinates in Fig. 1) into the southern Appalachians as far as Alabama (Hibbard, 2000), and east along the Greenland margin to Ellesmere Island (Trettin, 1987). This elongate east-west exposure of the arc system was all within a similar latitude band (Fig. 1).

PALEOGEOGRAPHY

Concerted efforts over decades of integrating geologic and paleomagnetic data have led to an understanding that from the Cambrian into the Ordovician, Laurentia's Appalachian margin was oriented east-west as the northern boundary

 Data Repository item 2017238 | doi:10.1130/G38985.1

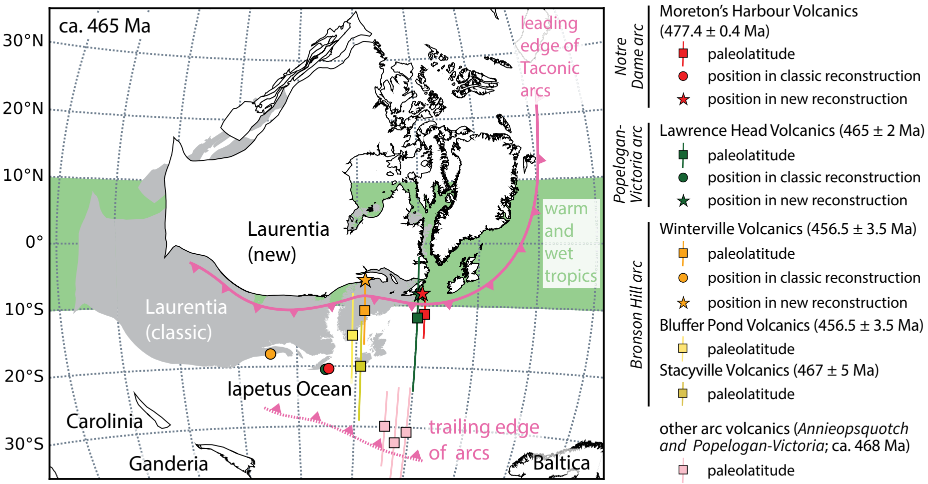

Figure 1. Paleogeographic reconstruction ca. 465 Ma, after the arrival of the leading edge of the Taconic arc system in the tropics along with the paleolatitude from allochthonous volcanic rocks shown with 95% confidence bounds. The reconstructed positions of these paleomagnetic localities are shown on the classic position of Laurentia (as in Torsvik and Cocks, 2017) and the new position proposed herein. While Laurentia must have been north of these volcanics, in the classic reconstruction their positions are south of the paleolatitudinal constraints rather than equatorward, as in the revised position. The positions of other continental blocks are as in Torsvik and Cocks (2017), other than Carolinia, which is modified to be traveling in unison with Ganderia.

of the Iapetus Ocean (Mac Niocaill et al., 1997). Although paleogeographic models typically place this margin south of 20°S in the relatively arid subtropics (Fig. 1), this position in the Ordovician is poorly constrained due to a lack of reliable paleomagnetic poles from cratonic Laurentia. In the comprehensive apparent polar wander path compilation of Torsvik et al. (2012), only two poles are included for the Ordovician: the St. George Group and Table Head Group limestones of Newfoundland. However, the Table Head Group limestones fail a conglomerate test (Hodych, 1989). Therefore, their remanence, and the similar remanence of the underlying St. George Group, must be the result of remagnetization. The Table Head Group rocks pass a fold test, indicating that remagnetization occurred prior to Devonian folding. Exclusion of these poles exacerbates an already large temporal gap between Laurentia poles in the Torsvik et al. (2012) compilation, such that there are no robust poles from the craton between the ca. 490 Ma Oneota Dolomite and the ca. 438 Ma Ringgold Gap poles (Fig. 2). The paleolatitudes implied by Cambrian and Silurian poles for Laurentia's distal margin (e.g., the New York and St. Lawrence promontories) are both in the subtropics (Fig. 2), and extrapolation between these poles (such as a spline fit; Torsvik et al., 2012) keeps Laurentia at a similar position through the Ordovician.

Given that there are no robust Ordovician paleomagnetic data from the Laurentian craton, we take the approach of using paleomagnetic data from well-dated volcanic rocks on the accreting terranes with magnetizations that are interpreted to be primary. Because the Appalachian margin must have been at or equatorward of these terranes, these data provide the best existing constraints on the Ordovician paleolatitude of Laurentia and have been interpreted to indicate the presence of peri-Laurentian, intra-Iapetan, and peri-Avalonian arc volcanism (Mac Niocaill et al., 1997). Open source

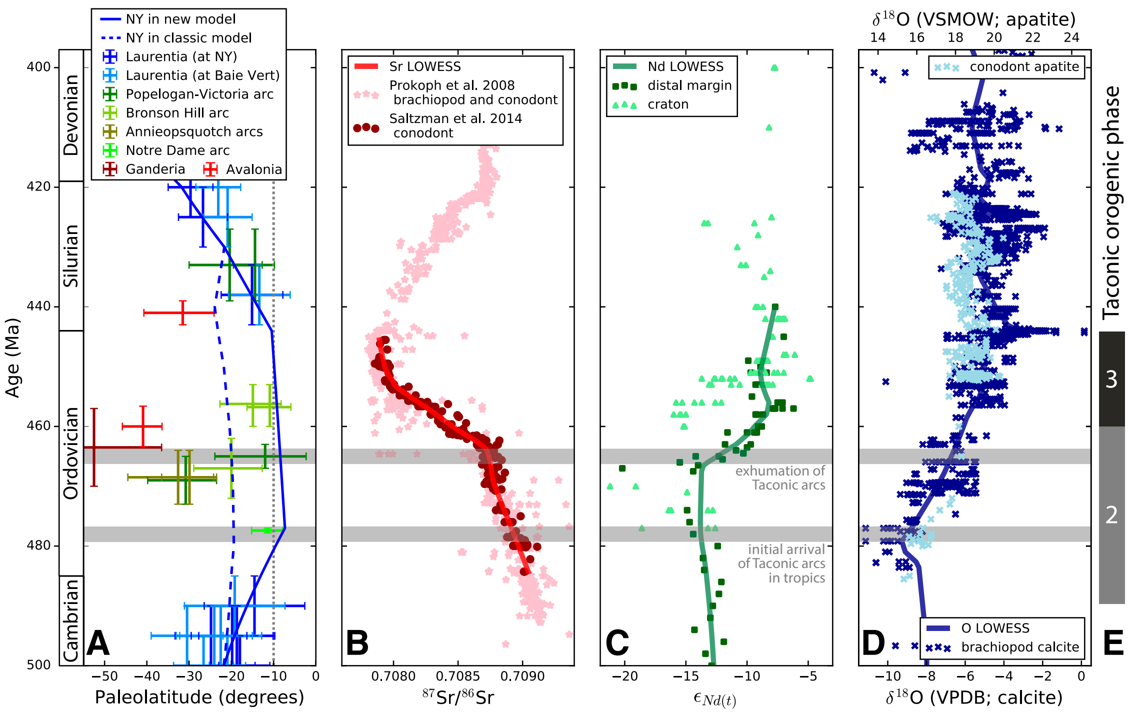

Figure 2. Paleomagnetic and geochemical data from 500 to 400 Ma. A: Paleolatitude constraints for Laurentia, Taconic arc terranes (Popelogan-Victoria, Bronson Hill, Annieopsquotch, and Notre Dame), and the peri-Gondwana Ganderia and Avalonia terranes. Laurentia paleolatitudes are calculated for two localities on the margin from paleomagnetic poles with the implied position of New York (NY) shown for the classic and new models. B: Strontium isotope data from conodont apatite and brachiopod calcite with a locally weighted scatterplot smoothing (LOWESS) regression curve to the data of Saltzman et al. (2014). C: Neodymium isotope data from fine-grained siliciclastic rocks on the Appalachian margin of Laurentia with a LOWESS curve for distal margin data. D: Oxygen isotope data from conodont apatite and brachiopod calcite with a LOWESS curve for the brachiopod data. VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water. E: Orogenic phases wherein Taconic 2 spans the collision of the leading edge of the arc system with promontories of the Laurentian margin. The peak of Taconic 2 coincides with arc exhumation in the tropics and weathering of ophiolite and arc detritus into Laurentian foreland basins. Late Ordovician arc accretion composes Taconic 3. Data sources are provided in the Data Repository (see footnote 1).

reconstructions developed in GPlates software (https://www.gplates.org/) for the evolution of the Iapetus Ocean (Domeier, 2016; Torsvik and Cocks, 2017) provide an excellent framework that can be modified with this approach.

In contrast to the Laurentian craton, eight robust Ordovician paleomagnetic data sets have been reported from accreted Taconic arc terranes through extensive efforts of the Rob Van der Voo research group at the University of Michigan (USA) (see the GSA Data Repository[1]). The interpretation of primary remanence in these volcanic rocks is variably based on dual polarities, positive fold tests, and interpretation of magnetic mineralogy. The oldest such locality is within the Notre Dame arc of Newfoundland, where ca. 477 Ma mafic volcanics of the Moreton's Harbour group yielded a paleolatitude of ~11°S (8°–15°S at 95% confidence) and were therefore interpreted to have formed in close proximity to Laurentia (Johnson et al., 1991). Four paleomagnetic localities from ca. 470–465 Ma volcanic rocks of the Victoria arc of Newfoundland provide paleolatitude constraints; the lowest latitude results are from the Lawrence Head volcanics, which were at ~12°S (2°–24°S at 95% confidence) (see the Data Repository). Similar aged pillow lavas from arc terranes in Newfoundland (the Annieopsquotch arcs in Fig. 2) give paleolatitudes of ~30°S that have been interpreted to indicate that they formed some distance from the margin within the Iapetus Ocean (Van der Voo et al., 1991). In New England (northeastern United States), ca. 467 Ma volcanics of the Bronson Hill arc yield a paleolatitude of ~20°S (12°–29°S at 95% confidence) while younger ca. 458 Ma volcanics give paleolatitudes of ~14°S (8°–23°S at 95% confidence) and ~11°S (6°–16°S at 95% confidence).

Although the Notre Dame arc was at a low latitude by ca. 475 Ma (Johnson et al., 1991) when it collided with hyperextended fragments of the Laurentian margin (Macdonald et al., 2014; van Staal and Barr, 2012), the Taconic seaway separated these terranes from the Laurentian autochthon until they were exhumed ca. 465 Ma. While the width of the Taconic seaway is unconstrained, the hyperextended margin of northeast Australia, which extends >500 km from the craton, may be a modern analog. This ~500-km-wide seaway closed between 475 and 465 Ma.

Paleolatitude constraints from ca. 470–465 Ma volcanics of the Taconic arc terranes span ~20° of latitude, suggesting a distended arc system comparable to the modern southwest Pacific (Fig. 1; Mac Niocaill et al., 1997). Although the precise latitudinal spread is difficult to resolve given uncertainty associated with paleolatitude estimates, we interpret the spread of these latitudes to represent the leading and trailing edges of the arc system (Fig. 1). This approach is a simplification; analogous to the modern southwest Pacific, there were probably other active subduction zones. Shortening during the Taconic and subsequent orogenies would have translated these terranes inward toward the craton, further contributing to the interpretation that Laurentia was equatorward of their paleolatitudes. Overall, the paleomagnetic database strongly supports a revised reconstruction wherein the Appalachian Laurentian margin was equatorward of 10°S at 465 Ma (Fig. 1).

WEATHERING PROXY DATA

Strontium and neodymium isotope data were compiled and recalculated (see the Data Repository) using *The Geological Time Scale 2012* (see Cooper and Sadler, 2012). $^{87}Sr/^{86}Sr$ data developed from the conodont apatite record a broad decline from 0.7090 to 0.7088 between 480 and 465 Ma. This gradual decline is followed by a sharp deflection at 465 Ma toward more juvenile $^{87}Sr/^{86}Sr$ values, reaching 0.7079 by 450 Ma (Saltzman et al., 2014; Fig. 2). Neodymium isotope (ε_{Nd}) data from fine-grained siliciclastic rocks deposited on the distal margin of Laurentia, on the Taconic allochthon, and Sevier basin (Gleason et al., 2002; Macdonald et al., 2017) display an inflection to more positive values at 465 Ma consistent with a substantial increase of sediment being weathered from juvenile lithologies (Fig. 2). This inflection in ε_{Nd} values occurs later in more interior basins (Fig. 2) that did not receive arc-derived sediment until subsequent accretionary events thrust arc rocks onto Laurentia between ca. 455 and 450 Ma (Macdonald et al., 2014, 2017).

DISCUSSION

The paleogeographic reconstruction presented here suggests that the Appalachian margin was at a significantly lower latitude than is typically depicted, equatorward of 10°S by 465 Ma (Fig. 1). Our reconstruction is compatible with paleomagnetic data from the Taconic arc system and is not in conflict with robust paleomagnetic poles from Laurentia.

We propose that the broad rise in oxygen isotope values and decline in strontium isotope values between 490 and 465 Ma (Fig. 2) are related to the movement of the Taconic arc system into the tropics and collision of the leading edge with distended fragments and promontories of the Laurentian margin (Taconic orogenic phase 2 of van Staal and Barr, 2012). A concomitant increase in global weatherability would have caused cooling through CO_2 drawdown, moderated by the silicate weathering feedback. In addition, we argue that the sharp drop in $^{87}Sr/^{86}Sr$ values, the shift toward more juvenile εNd values in shale from the distal margin of Laurentia, and the additional increase in oxygen isotope values between 465 and 455 Ma (Fig. 2) are due to the uplift and exhumation of the Taconic arc system in the tropics (peak of Taconic 2) followed by continued Late Ordovician arc accretion (Taconic 3). This exhumation led to uplift and erosion of island arc volcanics and suprasubduction ophiolites, as evidenced by the presence of detrital chromite in Middle to Late Ordovician foreland basins (e.g., Hiscott, 1978).

Increased weathering of volcanic arcs associated with the Taconic orogeny was previously invoked to explain the Ordovician drop in $^{87}Sr/^{86}Sr$ values (Young et al., 2009). The feasibility of this scenario was supported with a model in which global weatherability was increased by 25% and a new flux of riverine $^{87}Sr/^{86}Sr$ was introduced from weathering basalt with a composition of 0.7043 (Young et al., 2009). The ε_{Nd} compilation from the Appalachian margin of Laurentia, which records local provenance, is consistent with the hypothesis that the Taconic orogeny played a significant role in the inferred increase in global weatherability and riverine $^{87}Sr/^{86}Sr$ input to the ocean. The inflection in ε_{Nd} data from distal margin basins occurs a few million years prior to the inflection in the global $^{87}Sr/^{86}Sr$ curve (Fig. 2). This lead time is predicted if the weathering of Taconic terranes is a significant driver of the global strontium signal. Juvenile ε_{Nd} values should be imparted in siliciclastic rocks over the time scale that sediment transits from source to sink (~100 k.y.; Li et al., 2016), whereas strontium has a multimillion-year residence time in the ocean such that a prolonged interval of arc weathering would be necessary to significantly change seawater $^{87}Sr/^{86}Sr$ (Young et al., 2009). A complication in this interpretation is that the age model for the ε_{Nd} data is anchored by U-Pb zircon ages from ashes within the same stratigraphic sections (Macdonald et al., 2017), whereas the $^{87}Sr/^{86}Sr$ age model is based on Cooper and Sadler (2012; Saltzman et al., 2014), so the estimated temporal offset is as accurate as the calibration of the 2012 geological time scale.

Although other arc systems likely enhanced global weatherability in the Ordovician, such as those in the paleo–Asian Ocean and the Famatinian arc of present-day Argentina, the Taconic arcs likely played an outsized role as they were exhumed along an east-west belt in the tropics during the closure of the Iapetus Ocean (Fig. 1). Exhumation would have created significant topography composed of mafic and ultramafic lithologies through a wide swath across the tropics. This scenario has similarities to the low-latitude closure of the Neo-Tethys Ocean, and two-phase collision of the trans-Tethyan subduction system, which coincided with the two-pronged cooling trend from the Cretaceous to Oligocene (Jagoutz et al., 2016). The closure of major oceanic basins along east-west belts in the tropics may have been a significant driver of long-term

[1]GSA Data Repository item 2017238, details of the paleomagnetic and chemostratigraphic data compilations, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

cooling trends throughout Earth history. Following the Taconic orogeny, the Appalachian margin moved away from the tropics, so that collisions associated with the Salinic orogeny in the Silurian would have occurred at ~20°S, where there would have been a lesser effect on global weatherability (Fig. 2).

Lower pCO_2 resulting from elevated global weatherability could have set the stage for the growth of ice sheets during the Hirnantian. However, these tectonic boundary conditions may not be the sole driver for the Hirnantian ice advance, and other factors such as orbital forcing, changing ocean circulation, organic carbon burial, or rapid changes in albedo may have caused the shorter term cooling associated with the Hirnantian glacial maximum.

CONCLUSIONS

Our paleogeographic reconstruction, constrained by the paleolatitude of allochthonous volcanic rocks, demonstrates that Laurentia moved toward the equator during the Ordovician such that the Appalachian margin was equatorward of 10°S at 465 Ma. This movement into the tropics coincided with (1) collision and exhumation of the Taconic arc system marked by the appearance of detrital chromite in foreland basins; (2) a shift in ε_{Nd} data from fine-grained siliciclastic rocks on the Laurentian margin to more juvenile values; (3) a drop in seawater $^{87}Sr/^{86}Sr$ values to more juvenile values; and (4) a continued trend to higher values in the oxygen isotopic composition of both brachiopod carbonate and conodont phosphate. These data are consistent with tropical weathering of the Taconic arc-continent collision as a driver of Ordovician cooling.

REFERENCES CITED

Brenchley, P.J., Marshall, J.D., Carden, G.A.F., Robertson, D.B.R., Long, D.G.F., Meidla, T., Hints, L., and Anderson, T.F., 1994, Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period: Geology, v. 22, p. 295–298, doi:10.1130/0091-7613(1994)022<0295:BAIEFA>2.3.CO;2.

Buggisch, W., Joachimski, M.M., Lehnert, O., Bergström, S.M., Repetski, J.E., and Webers, G.F., 2010, Did intense volcanism trigger the first Late Ordovician icehouse?: Geology, v. 38, p. 327–330, doi:10.1130/G30577.1.

Cooper, R., and Sadler, P., 2012, The Ordovician Period, *in* Gradstein, F.M., et al., The geologic time scale 2012: Boston, Elsevier, v. 2, p. 489–524.

Dessert, C., Dupré, B., Gaillardet, J., François, L.M., and Allègre, C.J., 2003, Basalt weathering laws and the impact of basalt weathering on the global carbon cycle: Chemical Geology, v. 202, p. 257–273, doi:10.1016/j.chemgeo.2002.10.001.

Domeier, M., 2016, A plate tectonic scenario for the Iapetus and Rheic oceans: Gondwana Research, v. 36, p. 275–295, doi:10.1016/j.gr.2015.08.003.

Evans, D.A.D., 2006, Proterozoic low orbital obliquity and axial-dipolar geomagnetic field from evaporite palaeolatitudes: Nature, v. 444, p. 51–55, doi:10.1038/nature05203.

Gleason, J.D., Finney, S.C., and Gehrels, G.E., 2002, Paleotectonic implications of a mid- to late-Ordovician provenance shift, as recorded in sedimentary strata of the Ouachita and southern Appalachian mountains: Journal of Geology, v. 110, p. 291–304, doi:10.1086/339533.

Hibbard, J., 2000, Docking Carolina: Mid-Paleozoic accretion in the southern Appalachians: Geology, v. 28, p. 127–130, doi:10.1130/0091-7613(2000)28<127:DCMAIT>2.0.CO;2.

Hiscott, R.N., 1978, Provenance of Ordovician deep-water sandstones, Tourelle Formation, Quebec, and implications for initiation of the Taconic orogeny: Canadian Journal of Earth Sciences, v. 15, p. 1579–1597, doi:10.1139/e78-163.

Hodych, J.P., 1989, Limestones of western Newfoundland that magnetized before Devonian folding but after Middle Ordovician lithification: Geophysical Research Letters, v. 16, p. 93–96, doi:10.1029/GL016i001p00093.

Jagoutz, O., Macdonald, F.A., and Royden, L., 2016, Low-latitude arc-continent collision as a driver for global cooling: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 4935–4940, doi:10.1073/pnas.1523667113.

Johnson, R.J., van der Pluijm, B.A., and Van der Voo, R., 1991, Paleomagnetism of the Moreton's Harbour Group, northeastern Newfoundland Appalachians: Evidence for an Early Ordovician island arc near the Laurentian margin of Iapetus: Journal of Geophysical Research, v. 96, p. 11,689–11,701, doi:10.1029/91JB00870.

Kump, L.R., Arthur, M., Patzkowsky, M.E., Gibbs, M.E., Pinkus, M.T., and Sheehan, P.M., 1999, A weathering hypothesis for glaciation at high atmospheric pCO_2 during the Late Ordovician: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 152, p. 173–187, doi:10.1016/S0031-0182(99)00046-2.

Li, C., Yang, S., Zhao, J., Dosseto, A., Bi, L., and Clark, T.R., 2016, The time scale of river sediment source-to-sink processes in East Asia: Chemical Geology, v. 446, p. 138–146, doi:10.1016/j.chemgeo.2016.06.012.

Macdonald, F.A., Ryan-Davis, J., Coish, R.A., Crowley, J.L., and Karabinos, P., 2014, A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications for the Taconic orogeny and closure of the Iapetus Ocean: Geology, v. 42, p. 539–542, doi:10.1130/G35659.1.

Macdonald, F.A., Karabinos, P., Crowley, J.L., Hodgin, E.B., Crockford, P.W., and Delano, J.W., 2017, Bridging the gap between the foreland and the hinterland, II: Geochronology and tectonic setting of Ordovician magmatism and basin formation on the Laurentian margin of New England and Newfoundland: American Journal of Science, doi:10.2475/05.2017.02 (in press).

Mac Niocaill, C., van der Pluijm, B.A., and Van der Voo, R., 1997, Ordovician paleogeography and the evolution of the Iapetus ocean: Geology, v. 25, p. 159–162, doi:10.1130/0091-7613(1997)025<0159:OPATEO>2.3.CO;2.

McKenzie, N.R., Hughes, N.C., Gill, B.C., and Myrow, P.M., 2014, Plate tectonic influences on Neoproterozoic–early Paleozoic climate and animal evolution: Geology, v. 42, p. 127–130, doi:10.1130/G34962.1.

Prokoph, A., Shields, G.A., and Veizer, J., 2008, Compilation and time-series analysis of a marine carbonate $\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$ and $\delta^{34}S$ database through Earth history: Earth-Science Reviews, v. 87, p. 113–133.

Reusch, D.N., and Maasch, K.A., 1998, The transition from arc volcanism to exhumation, weathering of young Ca, Mg, Sr silicates, and CO_2 drawdown, *in* Crowley, T.J., and Burke, K.C., eds., Tectonic boundary conditions for climate reconstructions: Oxford Monographs on Geology and Geophysics no. 39, p. 261–276.

Saltzman, M.R., Edwards, C.T., Leslie, S.A., Dwyer, G.S., Bauer, J.A., Repetski, J.E., Harris, A.G., and Bergström, S.M., 2014, Calibration of a conodont apatite-based Ordovician $^{87}Sr/^{86}Sr$ curve to biostratigraphy and geochronology: Implications for stratigraphic resolution: Geological Society of America Bulletin, v. 126, p. 1551–1568, doi:10.1130/B31038.1.

Torsvik, T.H., and Cocks, L.R.M., 2017, Earth history and palaeogeography: Cambridge, UK, Cambridge University Press, 311 p., doi:10.1017/9781316225523.

Torsvik, T.H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J., Domeier, M., Gaina, C., and Tohver, E., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, v. 114, p. 325–368, doi:10.1016/j.earscirev.2012.06.007.

Trettin, H., 1987, Pearya: A composite terrane with Caledonian affinities in northern Ellesmere Island: Canadian Journal of Earth Sciences, v. 24, p. 224–245, doi:10.1139/e87-025.

Trotter, J.A., Williams, I.S., Barnes, C.R., Lécuyer, C., and Nicoll, R.S., 2008, Did cooling oceans trigger Ordovician biodiversification? Evidence from conodont thermometry: Science, v. 321, p. 550–554, doi:10.1126/science.1155814.

Van der Voo, R., Johnson, R.J., van der Pluijm, B.A., and Knutson, L.C., 1991, Paleogeography of some vestiges of Iapetus: Paleomagnetism of the Ordovician Robert's Arm, Summerford, and Chanceport groups, central Newfoundland: Geological Society of America Bulletin, v. 103, p. 1564–1575, doi:10.1130/0016-7606(1991)103<1564:POSVOI>2.3.CO;2.

van Staal, C., and Barr, S., 2012, Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin, *in* Percival, J.A., et al., eds., Tectonic styles in Canada: The Lithoprobe perspective: Geological Association of Canada Special Paper 49, p. 41–96.

Veizer, J., and Prokoph, A., 2015, Temperatures and oxygen isotopic composition of Phanerozoic oceans: Earth-Science Reviews, v. 146, p. 92–104, doi:10.1016/j.earscirev.2015.03.008.

Young, S.A., Saltzman, M.R., Foland, K.A., Linder, J.S., and Kump, L., 2009, A major drop in seawater $^{87}Sr/^{86}Sr$ during the middle Ordovician (Darriwilian): Links to volcanism and climate?: Geology, v. 37, p. 951–954, doi:10.1130/G30152A.1.

Manuscript received 23 January 2017
Revised manuscript received 11 April 2017
Manuscript accepted 19 April 2017

Printed in USA

THE GEOLOGICAL SOCIETY
OF AMERICA®

RESEARCH **FOCUS**

Silicate weathering, volcanic degassing, and the climate tug of war

Matthew R. Saltzman
School of Earth Sciences, The Ohio State University, Columbus, Ohio 43210, USA

Long-term climate change is controlled primarily by the balance between CO_2 sources from volcanic and metamorphic degassing and by sinks tied to both silicate weathering and, to a lesser extent, organic carbon burial. Whereas a recent paper by McKenzie et al. (2016) argues that continental arc volcanism is the principal driver of greenhouse-icehouse transitions over the past ~720 m.y., in this issue of *Geology*, Swanson-Hysell and Macdonald (2017) bolster the idea that cooling and ice buildup can be driven by changes in silicate weathering, provided that the right rock (calcium-rich, mafic arc) is uplifted in the right place (warm, wet tropics). Each side of the source-sink coin is associated with imperfect geologic proxies. In the case of the degassing flux, detrital zircon geochronology may potentially reveal variations through time; low sedimentary proportions of young zircons, which form in melts concentrated along continental subduction zones, suggest low CO_2 fluxes (Lee et al., 2015; McKenzie et al., 2016). For silicate weathering, radiogenic isotopes studies (e.g., Sr, Nd, Li) of sedimentary successions provide information on changes in the age or composition of source rocks undergoing weathering (probably yielding only limited information about rates of weathering) (Kump and Arthur, 1997; Bataille et al., 2017). As with most geochemical proxies, each individual radiogenic isotope curve is of limited value on its own but gains interpretive strength when combined with others.

It is generally agreed upon that there are three greenhouse-icehouse transitions in the Phanerozoic (Paleogene, Late Paleozoic, and end-Ordovician). For the Paleogene, it was proposed (Raymo et al., 1988) that the Himalayan uplift affected CO_2 sinks through enhanced silicate weathering interpreted in part from a prominent increase in seawater $^{87}Sr/^{86}Sr$, although disentangling the role of carbonate weathering remains a vexing problem (Jacobson et al., 2002). Furthermore, constraints imposed by carbon-cycle mass balance require that if silicate weathering rates did increase locally in uplifted regions of the Himalaya, this must be quickly (over time scales greater than ~10,000 years) balanced out by a decrease in silicate weathering elsewhere on Earth's surface, such that net global weathering rates effectively match degassing (Kump and Arthur, 1997). If CO_2 degassing and silicate weathering were not in balance on these time scales, excessively large fluctuations could lead to a complete loss of atmospheric CO_2 on Earth. More recent Cenozoic studies have examined both the role of declining degassing (Mills et al., 2014), perhaps associated with reduction in continental arc volcanism (McKenzie et al., 2016), and arc weathering in the tropics (Jagoutz et al., 2016). The Late Paleozoic greenhouse-icehouse transition has been attributed to a lowering of atmospheric CO_2 levels brought about, in part, by the rise of land plants and their effect on silicate weathering and organic carbon burial (Berner, 2004), although this issue is far from settled (Montañez and Poulsen, 2013).

Arguably the most problematic icehouse transition has always been the Hirnantian (end-Ordovician) glaciation, which appears as a relatively short-lived cooling within a strong greenhouse interval. As such, it has been difficult for models to get CO_2 levels low enough to make ice (Berner, 2004). Everything "under the sun" has been proposed: Brenchley et al. (1994) emphasized organic carbon burial, Kump et al. (1999) and Young et al. (2009) drew attention to Late Ordovician tectonic uplift and silicate weathering in relation to degassing, Nardin et al. (2011) pointed to paleogeography and continental positioning, Lenton et al. (2012) discussed the role of early plants on silicate weathering and organic carbon burial, and Herrmann et al. (2004) and Pohl et al. (2016) addressed the importance of thresholds in pCO_2 in relation to ocean circulation and sea level. The list goes on. Rigorous testing of these hypotheses has limitations though; how well do we really know when the cooling and ice buildup began (e.g., Pope and Steffen, 2003; Saltzman and Young, 2005; Rasmussen et al., 2016)? The Swanson-Hysell and Macdonald paper won't end the debate over the Ordovician icehouse transition, but it does bring into focus the critical role that regional tectonics, paleogeography, and continental arc weathering must have played.

A struggle that anyone who works on the long-term carbon cycle has faced is bridging the gap between the evidence for changes in Earth's climate (studied by sedimentary geologists) and the direct evidence for the tectonic changes that produce them (structural, igneous, and metamorphic geology). Swanson-Hysell and Macdonald show us the fruits of an integrated study that links these generally distinct sets of literature, in their case involving paleomagnetic evidence for the latitudinal positioning of Ordovician volcanic source rocks (their figure 1) and geochemical study of coeval sedimentary rocks (their figure 2). In large part, their paper is a synthesis of existing data, which allows for the most holistic view to date of the problems posed by the Ordovician icehouse transition. Previous studies have recognized the importance of coupled strontium ($^{87}Sr/^{86}Sr$) and neodymium (ε_{Nd}) isotope stratigraphy, which can simultaneously address changes in global and local silicate weathering, but Swanson-Hysell and Macdonald are the first to showcase this approach for the Ordovician in their groundbreaking paper that complements the recent Neoproterozoic efforts of Cox et al. (2016).

The Ordovician convergence of the Iapetus ocean resulted in arc volcanism along the Laurentian continental margin (e.g., van Staal and Hatcher, 2010), but linking the weathering of these arc volcanics (i.e., Bronson Hill, Notre Dame, and Popelogan-Victoria arcs) to global climate is the challenge taken up by Swanson-Hysell and Macdonald. Young et al. (2009), building on the ideas of Kump et al. (1999) and Shields et al. (2003), examined the role of arc volcanic weathering based on a rapid decrease in the global seawater $^{87}Sr/^{86}Sr$ (see also Berner, 2006) and noted that ε_{Nd} changes were consistent with an Appalachian (Taconic) weathering signature (Gleason et al., 2002; Wright et al., 2002). However, the question of whether the latitudinal distribution of the Taconic arc volcanics was appropriately warm and wet, and demonstration of expected leads and lags in $^{87}Sr/^{86}Sr$ and ε_{Nd} trends, were not addressed by Young et al. (2009). Swanson-Hysell and Macdonald painstakingly demonstrate with paleomagnetic data that arc volcanics along the Appalachian margin were within the warm and wet tropics where chemical weathering rates are highest, and not the arid subtropics as previously published. Furthermore, they show that the onset of a prominent Ordovician $^{87}Sr/^{86}Sr$ seawater fall beginning at ca. 464 Ma, which occurs at a rate (0.0001/m.y.) that is among the steepest in the entire Phanerozoic (Saltzman et al., 2014), lags the ε_{Nd} shift in a manner predicted by much the shorter sediment source-to-sink transit time of Nd compared to the residence time of Sr in the oceans.

Like any innovative paper, Swanson-Hysell and Macdonald's work raises as many questions as it answers. Did the Taconic arc-continent collision occur in the wet tropics as opposed to arid subtropics? Yes, and more generally this can explain why only some arc-continent collisions can drive icehouse transitions. Still, some caution is warranted in the actual proxy evidence for enhanced Taconic weathering, because while the ε_{Nd} increase demonstrates unequivocally that continental weathering shifted to younger source rocks at ca. 464 Ma in the Appalachian region (and later in more cratonal portions of Laurentia), an Ordovician arc volcanic end member is difficult to unambiguously detect using Nd isotopes in sediments which fall within the range of values expected for Grenville crust (Bock et al., 1998; Gleason et al., 2002). Similarly, because Swanson-Hysell and Macdonald rely on measurements of ε_{Nd} from clastic sediments (dated using U-Pb zircon ages) and $^{87}Sr/^{86}Sr$ from carbonate-dominated successions (relying on conodont biostratigraphy), they acknowledge that there is ambiguity in the proposed lead-lag relationship. Lastly, the existing Ordovician $\delta^{18}O$ paleotemperature curve is relatively poorly constrained in the interval of changing ε_{Nd} and $^{87}Sr/^{86}Sr$, leaving open questions about the extent to which theoretical cooling matches actual cooling. In order to be consistent with the paleotemperature curve of Trotter et al. (2008), Young et al. (2009) balanced enhanced weathering with increased degassing until the end of the Ordovician (mid-late Katian). Without more highly resolved constraints on the degassing flux and leads and lags in the isotope curves, a consensus view of the cause(s) of the Ordovician greenhouse-icehouse transition will likely remain elusive. Ultimately, integration of radiogenic isotope records with detrital zircon records may allow us to tap into the promise of studying the sedimentary and volcanic records in parallel throughout geologic history.

REFERENCES CITED

Berner, R.A., 2004, The Phanerozoic Carbon Cycle: CO_2 and O_2: Oxford, UK, Oxford University Press, 150 p.

Berner, R.A., 2006, Inclusion of the weathering of volcanic rocks in the GEOCARBSULF model: American Journal of Science, v. 306, p. 295–302, doi:10.2475/05.2006.01.

Bataille, C.P., Willis, A., Yang, X., and Liu, X.-M., 2017, Continental igneous rock composition: A major control of past global chemical weathering: Science Advances, v. 3, p. e1602183, doi:10.1126/sciadv.1602183.

Bock, B., McLennan, S.M., and Hanson, G.N., 1998, Geochemistry and provenance of the middle Ordovician Austin Glen member (Normanskill formation) and the Taconian orogeny in New England: Sedimentology, v. 45, p. 635–655, doi:10.1046/j.1365-3091.1998.00168.x.

Brenchley, P.J., Marshall, J.D., Carden, G.A.F., Robertson, D.B.R., Long, D.G.F., Meidla, T., Hints, L., and Anderson, T.F., 1994, Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period: Geology, v. 22, p. 295–298, doi:10.1130/0091-7613(1994)022<0295:BAIEFA>2.3.CO;2.

Cox, G.M., Halverson, G.P., Stevenson, R.K., Vokaty, M., Poirier, A., Kunzmann, M., Li, Z.-X., Denyszyn, S.W., Strauss, J.V., and Macdonald, F.A., 2016, Continental flood basalt weathering as a trigger for Neoproterozoic snowball earth: Earth and Planetary Science Letters, v. 446, p. 89–99, doi:10.1016/j.epsl.2016.04.016.

Gleason, J.D., Finney, S.C., and Gehrels, G.E., 2002, Paleotectonic implications of a Mid- to Late-Ordovician provenance shift, as recorded in sedimentary strata of the Ouachita and Southern Appalachian Mountains: The Journal of Geology, v. 110, p. 291–304, doi:10.1086/339533.

Herrmann, A.D., Haupt, B.J., Patzkowsky, M.E., Seidov, D., and Slingerland, R.L., 2004, Response of Late Ordovician paleoceanography to changes in sea level, continental drift, and atmospheric pCO_2: Potential causes for long-term cooling and glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 210, p. 385–401, doi:10.1016/j.palaeo.2004.02.034.

Jacobson, A.D., Blum, J.D., and Walter, L.M., 2002, Reconciling the elemental and Sr isotope composition of Himalayan weathering fluxes: Insights from the carbonate geochemistry of stream waters: Geochimica et Cosmochimica Acta, v. 66, p. 3417–3429, doi:10.1016/S0016-7037(02)00951-1.

Jagoutz, O., Macdonald, F.A., and Royden, L., 2016, Low-latitude arc–continent collision as a driver for global cooling: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 4935–4940, doi:10.1073/pnas.1523667113.

Kump, L.R., and Arthur, M.A., 1997, Global chemical erosion during the Cenozoic: Weatherability balances the budgets, *in* Ruddiman, W.F., ed., Tectonic uplift and climate change: New York, Plenum Press, p. 399–426, doi:10.1007/978-1-4615-5935-1_18.

Kump, L.R., Arthur, M.A., Patzkowsky, M.E., Gibbs, M.T., Pinkus, D.S., and Sheehan, P.M., 1999, A weathering hypothesis for glaciation at high atmospheric pCO_2 during the Late Ordovician: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 152, p. 173–187, doi:10.1016/S0031-0182(99)00046-2.

Lee, C.-T.A., Thurner, S., Paterson, S., and Cao, W., 2015, The rise and fall of continental arcs: interplays between magmatism, uplift, weathering, and climate: Earth and Planetary Science Letters, v. 425, p. 105–119, doi:10.1016/j.epsl.2015.05.045.

Lenton, T.M., Crouch, M., Johnson, M., Pires, N., and Dolan, L., 2012, First plants cooled the Ordovician: Nature Geoscience, v. 5, p. 86–89, doi:10.1038/ngeo1390.

McKenzie, N.R., Horton, B.K., Loomis, S.E., Stockli, D.F., Planavsky, N.J., and Lee, C.-T.A., 2016, Continental arc volcanism as the principal driver of icehouse-greenhouse variability: Science, v. 352, p. 444–447, doi:10.1126/science.aad5787.

Mills, B., Daines, S.J., and Lenton, T.M., 2014, Changing tectonic controls on the long-term carbon cycle from Mesozoic to present: Geochemistry Geophysics Geosystems, v. 15, p. 4866–4884, doi:10.1002/2014GC005530.

Montañez, I.P., and Poulsen, C.J., 2013, The Late Paleozoic Ice Age: An Evolving Paradigm: Annual Review of Earth and Planetary Sciences, v. 41, p. 629–656, doi:10.1146/annurev.earth.031208.100118.

Nardin, E., Goddéris, Y., Donnadieu, Y., Le Hir, G., Blackey, R.C., Pucéat, E., and Aretz, M., 2011, Modeling the early Paleozoic long-term climatic trend: Geological Society of America Bulletin, v. 123, p. 1181–1192, doi:10.1130/B30364.1.

Pohl, A., Nardin, E., Vandenbroucke, T.R.A., and Donnadieu, Y., 2016, High dependence of Ordovician ocean surface circulation on atmospheric CO_2 levels: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 458, p. 39–51, doi:10.1016/j.palaeo.2015.09.036.

Pope, M.C., and Steffen, J.B., 2003, Widespread, prolonged late Middle to Late Ordovician upwelling in North America: A proxy record of glaciation?: Geology, v. 31, p. 63–66, doi:10.1130/0091-7613(2003)031<0063:WPLMTL>2.0.CO;2.

Rasmussen, C.M.Ø., et al., 2016, Onset of the main Phanerozoic marine radiation sparked by emerging Mid Ordovician icehouse: Nature Scientific Reports, v. 6, p. 18884, doi:10.1038/srep18884.

Raymo, M.E., Ruddiman, W.F., and Froelich, P.N., 1988, Influence of late Cenozoic mountain building on ocean geochemical cycles: Geology, v. 16, p. 649–653, doi:10.1130/0091-7613(1988)016<0649:IOLCMB>2.3.CO;2.

Saltzman, M.R., and Young, S.A., 2005, A long-lived glaciation in the Late Ordovician?: Isotopic and sequence stratigraphic evidence from western Laurentia: Geology, v. 33, p. 109–112, doi:10.1130/G21219.1.

Saltzman, M.R., Edwards, C.T., Leslie, S.A., Dwyer, G.S., Bauer, J.A., Repetski, J., Harris, A., and Bergström, S.M., 2014, Calibration of a conodont apatite-based Ordovician $^{87}Sr/^{86}Sr$ curve to biostratigraphy and geochronology: Implications for stratigraphic resolution: Geological Society of America Bulletin, v. 126, p. 1551–1568, doi:10.1130/B31038.1.

Shields, G.A., Carden, G.A., Veizer, J., Meidla, T., Rong, J., and Li, R., 2003, Sr, C, and O isotope geochemistry of Ordovician brachiopods: A major isotopic event around the Middle-Late Ordovician transition: Geochimica et Cosmochimica Acta, v. 67, p. 2005–2025, doi:10.1016/S0016-7037(02)01116-X.

Swanson-Hysell, N.L., and Macdonald, F.A., 2017, Tropical weathering of the Taconic orogeny as a driver for Ordovician cooling: Geology, v. 45, p. 719–722, doi:10.1130/G38985.1

Trotter, J.A., Williams, I.S., Barnes, C.R., Lécuyer, C., and Nicoll, R.S., 2008, Did cooling oceans trigger Ordovician biodiversification? Evidence from conodont thermometry: Science, v. 321, p. 550–554.

van Staal, C.R., and Hatcher, R.D., Jr., 2010, Global setting of Ordovician orogenesis, *in* Finney, S.C., and Berry W.B.N., eds., The Ordovician Earth System: Geological Society of America Special Papers, v. 466, p. 1–11, doi:10.1130/2010.2466(01).

Wright, C.A., Barnes, C.R., and Jacobsen, S.B., 2002, Neodymium isotopic composition of Ordovician conodonts as a seawater proxy: Testing paleogeography: Geochemistry Geophysics Geosystems, v. 3, doi:10.1029/2001GC000195.

Young, S.A., Saltzman, M.R., Foland, K., Linder, J., and Kump, L., 2009, A major drop in seawater $^{87}Sr/^{86}Sr$ during the Middle Ordovician (Darriwilian): Links to volcanism and climate?: Geology, v. 37, p. 951–954, doi:10.1130/G30152A.1.

Printed in USA