GSA Data Repository 2020038

Balseiro, D., and Powell, M.G., 2020, Carbonate collapse and the late Paleozoic ice age marine biodiversity crisis: Geology, v. 48, https://doi.org/10.1130/G46858.1

SUPPORTING INFORMATION

Climate of the Late Paleozoic Ice Age. The LPIA was an intensification of an extended period of global cooling that began in the Devonian (Le Hir et al., 2011). Its onset in the latest Visean-early Serpukhovian (Smith and Read, 2000; Davies, 2008; Frank et al., 2015) was likely triggered by the formation of Pangea in the late Mississippian (Nance and Linnemann, 2008), as erosion of the newly uplifted Ouachita-Variscan-Alleghenian orogen caused atmospheric pCO_2 to fall (Goddéris et al., 2017). Volcanism associated with the Pangean collisions may also have contributed to cooling by increasing stratospheric sulfur which would have decreased radiative forcing (Soreghan et al., 2019). Oxygen isotopes of brachiopod shells suggest that tropical ocean temperatures cooled by ~5-10°C when the LPIA began (Mii et al., 2001; Giles, 2012), a shift that is equivalent in today's ocean to the difference in average sea-surface temperatures between 0° and ~30° latitude.

Marine species had not only to contend with colder ocean temperatures, but also repeated changes in habitable area caused by sea level fluctuations. An immediate consequence of global cooling was an initial eustatic fall of >100 m that caused an unconformity of nearly global extent (Saunders and Ramsbottom, 1986). This was followed by orbitally-paced, high-amplitude glacio-eustatic fluctuations throughout the LPIA (Horton et al., 2012). These changes would have been exacerbated by the loss of shallow shelf area on continental margins from the Pangean collision.

The traditional view of the LPIA as a single, prolonged south polar ice cap has given way to a more complex understanding of the event as a series of glacial pulses, as regional ice centers waxed and waned asynchronously across Gondwana. These pulses, which each lasted ~1-8 m.y. (Fielding et al., 2008), were accompanied by temperature shifts of ~4-7°C (Montañez et al., 2007). As a result, we expect that the biotic effects of the LPIA should be highly regional, which is attested by paleoecological studies in specific regions (e.g., Powell, 2008; Heim, 2009; Bonelli and Patzkowsky, 2011; Badyrka et al., 2013; Balseiro, 2016).

Once thick soil cover was re-established following erosion of the orogen, and Permian climate became more arid, atmospheric pCO_2 rose once again and ended the LPIA (Goddéris et al., 2017). Paleosol chemistry suggests a temperature rise in the terrestrial tropics of ~13°C as the LPIA ended in the Early Permian (Tabor et al., 2013), in general agreement with the results of climate models (Poulsen et al., 2007). However, regional ice centers persisted throughout the Permian at southern high latitudes (Frank et al., 2015).

Methods. The raw data obtained from the Paleobiology Database (https://paleobiodb.org/) consisted of 43,282 occurrences, of which 65% were Brachiopoda, 29% were Mollusca, and 6% were Cnidaria. Altogether, these three taxa constitute the majority of Famennian-Changsinghian occurrences (69%, as downloaded on 01 August 2019 from https://paleobiodb.org/data1.2/occs/list.csv?datainfo&rowcount&interval=Famennian,Changhsingian&cc=NOA&envtype=marine). Although mollusks were proportionally better represented in siliciclastic environments (34.7% of occurrences) than either brachiopods (18.8%) or cnidarians (17.6%), as expected (Kiessling and Aberhan, 2007), each taxon was well represented in both carbonate and siliciclastic environments, reducing the possibility that one taxon could drive the overall trend. All three taxa independently show consistent trends in diversity across the LPIA (decrease in diversity within carbonate environments coupled with increase in diversity within siliciclastic environments) (Fig. S1).

Occurrences were then assigned to 11 temporal bins that combined stages when necessary to achieve adequate sample size (Fig. S2). Each occurrence was then matched to one of 4,241 North American marine lithologic units obtained from Macrostrat (https://macrostrat.org/), based on collection number. Occurrences were associated with a specific lithology (carbonate, siliciclastic, or other) and a specific realm (marine, terrestrial, or transitional), based on the relevant fields in the PBDB and Macrostrat. Only marine data were retained for analysis. The final data set consisted of 30,346 North American marine fossil occurrences that were assignable to a specific lithology (carbonate or siliciclastic) and specific Macrostrat unit. After matching occurrences to Macrostrat units, there were too few Late Permian (Wuchiapingian-Changhsingian) occurrences to obtain meaningful results. The Late Permian was therefore excluded from diversity analyses that required per-interval diversity estimates.

Macrostrat divides the stratigraphic record into “units”, which are portions of geologic formations that fall within a particular “column” (geographic region). We calculated rock volume for each interval by multiplying the stratigraphic thickness of each unit by the area of the Macrostrat column in which it occurred, and then summing the volume of all units in a time interval. For units that crossed stratigraphic boundaries, we proportionally allocated unit volumes using the top and bottom age fields in Macrostrat, which were estimated (by Macrostrat) from a continuous time age model (Peters et al., 2018). Because units vary in thickness, we obtained 95% confidence intervals around rock volumes by iterative random sampling of stratigraphic thicknesses from the range given for each unit. Carbonate and siliciclastic rock volumes were obtained by multiplying unit volumes by the lithologic proportion recorded in Macrostrat. Carbonate and siliciclastic rocks account for 89% of all late Paleozoic rocks by volume.

We used the information recorded in the PBDB for the lithological assignation of each occurrence. PBDB records up to two main lithologies per occurrence/collection. We first characterized either lithology as carbonate or siliciclastic. We then discarded all occurrences coming from mixed lithologies (i.e., carbonate in one lithology field and siliciclastic in the other) that did not positively identified the actual lithology where the fossils came from. Hence only occurrences undoubtedly coming from carbonates or siliciclastics were used. Carbonates were defined as lithologies containing the words "carbonate", "limestone", "reef rocks", "bafflestone" "bindstone", "dolomite", "framestone", "grainstone" "lime mudstone", "packstone", "rudstone", "wackestone". Siliciclastics were defined as lithologies containing the words "shale", "siliciclastic", "breccia", "claystone", "conglomerate", "gravel", "mudstone", "quartzite", "sandstone", "siltstone", "slate".

We defined landscapes as Macrostrat units that recorded more than 70% of a given lithology (siliciclastic or carbonate). Such definition implies that the given lithology at least doubles the volume of the remaining lithologies. Less conservative approaches for defining landscapes, such as more than 50% of the given lithology, gives almost identical results. Carbonates beds within siliciclastic units were defined based on PBDB lithological information (collections from carbonate lithology, within a predominantly siliciclastic Macrostrat unit).

Fisher's alpha is commonly used by biologists to estimate sample-standardized diversity (Hayek and Buzas, 2010). The diversity parameter, α, is related to the number of species, S, and the number of individuals, N, by $S = \alpha * \ln(1 + N/\alpha)$. Fisher's α (Fisher et al., 1943) should not be confused with alpha diversity, which is mean species richness within a local area (Whittaker, 1972). SQS is a type of coverage-based rarefaction that is increasingly used by paleontologists (Alroy, 2010). Our results are essentially the same using either metric, which, for our data, are highly correlated ($n = 10$, $r = 0.97$, 95% CI [0.87, 0.99], $p < 0.001$). We have reported Fisher's α rather than SQS because the quorum required for a particular analysis varies depending on which data are included, and the quorum is necessarily low (0.4). Therefore, Fisher's α provides more consistently interpretable results across analyses than SQS in this case.

All analyses were performed in R (https://www.R-project.org/).

SUPPLEMENTAL FIGURES

Figure S1. Trends in sample-standardized genus diversity in all (black), carbonate (blue), and siliciclastic (red) environments through the Late Paleozoic, for Brachiopoda, Mollusca, and Cnidaria.

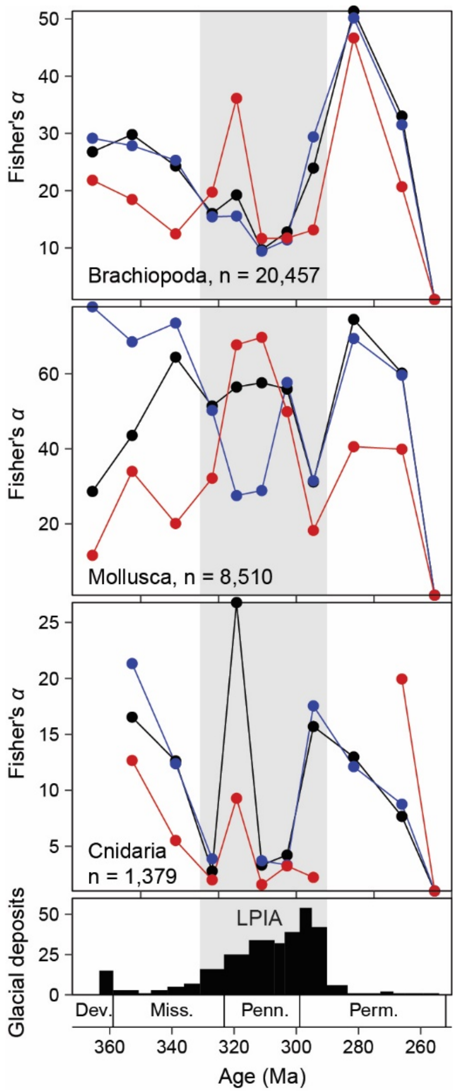
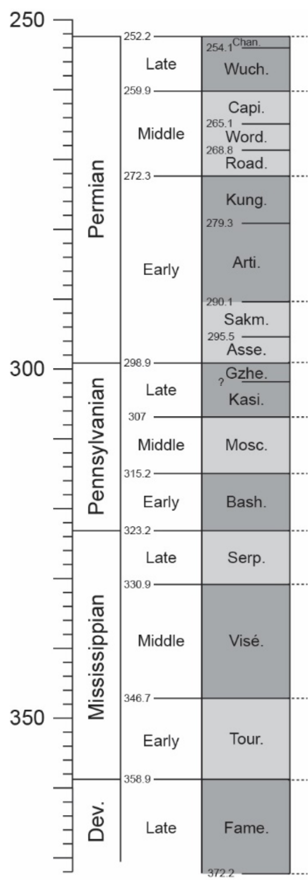


Figure S2. Timescale used in this study.



ADDITIONAL REFERENCES CITED

Alroy, J., 2010, Geographical, Environmental and Intrinsic Biotic Controls on Phanerozoic Marine Diversification: Controls on Phanerozoic Marine Diversification: Palaeontology, v. 53, p. 1211–1235, doi:10.1111/j.1475-4983.2010.01011.x.

Badyrka, K., Clapham, M.E., and López, S., 2013, Paleoecology of brachiopod communities during the late Paleozoic ice age in Bolivia (Copacabana Formation, Pennsylvanian–Early Permian): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 387, p. 56–65, doi:10.1016/j.palaeo.2013.07.016.

Balseiro, D., 2016, Compositional turnover and ecological changes related to the waxing and waning of glaciers during the late Paleozoic ice age in ice-proximal regions (Pennsylvanian, western Argentina): Paleobiology, v. 42, p. 335–357, doi:10.1017/pab.2015.53.

Bonelli, J.R., and Patzkowsky, M.E., 2011, Taxonomic and Ecologic Persistence Across the Onset of the Late Paleozoic Ice Age: Evidence from the Upper Mississippian (chesterian Series), Illinois Basin, United States: PALAIOS, v. 26, p. 5–17, doi:10.2110/palo.2010.p10-013r.

Davies, S.J., 2008, The record of Carboniferous sea-level change in low-latitude sedimentary successions from Britain and Ireland during the onset of the late Paleozoic ice age, *in* Resolving the Late Paleozoic Ice Age in Time and Space, Geological Society of America Boulder, v. 441, p. 187–204.

Fielding, C.R., Frank, T.D., and Isbell, J.L., 2008, The late Paleozoic ice age—A review of current understanding and synthesis of global climate patterns, *in* Special Paper 441: Resolving the Late Paleozoic Ice Age in Time and Space, Geological Society of America, v. 441, p. 343–354, doi:10.1130/2008.2441(24).

Fisher, R.A., Corbet, A.S., and Williams, C.B., 1943, The relation between the number of species and the number of individuals in a random sample of an animal population: The Journal of Animal Ecology, p. 42–58.

Frank, T.D., Shultis, A.I., and Fielding, C.R., 2015, Acme and demise of the late Palaeozoic ice age: A view from the southeastern margin of Gondwana: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 418, p. 176–192, doi:10.1016/j.palaeo.2014.11.016.

Giles, P.S., 2012, Low-latitude Ordovician to Triassic brachiopod habitat temperatures (BHTs) determined from δ18O[brachiopod calcite]: A cold hard look at ice-house tropical oceans: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 317–318, p. 134–152, doi:10.1016/j.palaeo.2012.01.002.

Goddéris, Y., Donnadieu, Y., Carretier, S., Aretz, M., Dera, G., Macouin, M., and Regard, V., 2017, Onset and ending of the late Palaeozoic ice age triggered by tectonically paced rock weathering: Nature Geoscience, v. 10, p. 382–386, doi:10.1038/ngeo2931.

Hayek, L.-A.C., and Buzas, M.A., 2010, Surveying Natural Populations: Quantitative Tools for Assessing Biodiversity: Columbia University Press, 618 p.

Heim, N.A., 2009, Stability of regional brachiopod diversity structure across the Mississippian/Pennsylvanian boundary: Paleobiology, v. 35, p. 393–412, doi:10.1666/0094-8373-35.3.393.

Horton, D.E., Poulsen, C.J., Montañez, I.P., and DiMichele, W.A., 2012, Eccentricity-paced late Paleozoic climate change: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 331–332, p. 150–161, doi:10.1016/j.palaeo.2012.03.014.

Kiessling, W., and Aberhan, M., 2007, Environmental Determinants of Marine Benthic Biodiversity Dynamics through Triassic-Jurassic Time: , p. 22.

Le Hir, G., Donnadieu, Y., Goddéris, Y., Meyer-Berthaud, B., Ramstein, G., and Blakey, R.C., 2011, The climate change caused by the land plant invasion in the Devonian: Earth and Planetary Science Letters, v. 310, p. 203–212, doi:10.1016/j.epsl.2011.08.042.

Mii, H.-S., Grossman, E.L., Yancey, T.E., Chuvashov, B., and Egorov, A., 2001, Isotopic records of brachiopod shells from the Russian Platform — evidence for the onset of mid-Carboniferous glaciation: Chemical Geology, v. 175, p. 133–147, doi:10.1016/S0009-2541(00)00366-1.

Montañez, I.P., Tabor, N.J., Niemeier, D., DiMichele, W.A., Frank, T.D., Fielding, C.R., Isbell, J.L., Birgenheier, L.P., and Rygel, M.C., 2007, CO2-Forced Climate and Vegetation Instability During Late Paleozoic Deglaciation: Science, v. 315, p. 87–91, doi:10.1126/science.1134207.

Nance, R.D., and Linnemann, U., 2008, The Rheic Ocean: origin, evolution, and significance: GSA today, v. 18, p. 4–12.

Peters, S.E., Husson, J.M., and Czaplewski, J., 2018, Macrostrat: A Platform for Geological Data Integration and Deep-Time Earth Crust Research: Geochemistry, Geophysics, Geosystems, v. 19, p. 1393–1409, doi:10.1029/2018GC007467.

Poulsen, C.J., Pollard, D., Montañez, I.P., and Rowley, D., 2007, Late Paleozoic tropical climate response to Gondwanan deglaciation: Geology, v. 35, p. 771, doi:10.1130/G23841A.1.

Powell, M.G., 2008, Timing and selectivity of the Late Mississippian mass extinction of brachiopod genera from the Central Appalachian Basin: PALAIOS, v. 23, p. 525–534, doi:10.2110/palo.2007.p07-038r.

Saunders, W.B., and Ramsbottom, W.H.C., 1986, The mid-Carboniferous eustatic event: Geology, v. 14, p. 208, doi:10.1130/0091-7613(1986)14<208:TMEE>2.0.CO;2.

Smith, L.B., and Read, J.F., 2000, Rapid onset of late Paleozoic glaciation on Gondwana: Evidence from Upper Mississippian strata of the Midcontinent, United States: Geology, v. 28, p. 279–282, doi:10.1130/0091-7613(2000)28<279:ROOLPG>2.0.CO;2.

Soreghan, G.S., Soreghan, M.J., and Heavens, N.G., 2019, Explosive volcanism as a key driver of the late Paleozoic ice age: Geology, v. 47, p. 600–604, doi:10.1130/G46349.1.

Tabor, N.J., DiMichele, W.A., Montañez, I.P., and Chaney, D.S., 2013, Late Paleozoic continental warming of a cold tropical basin and floristic change in western Pangea: International Journal of Coal Geology, v. 119, p. 177–186, doi:10.1016/j.coal.2013.07.009.

Whittaker, R.H., 1972, Evolution and Measurement of Species Diversity: TAXON, v. 21, p. 213–251, doi:10.2307/1218190.